Watershed Modeling and Best Management Practices Decision Support using Geoinformatics and Soft Computing

THESIS

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

SHUBHAM AGGARWAL

Under the Supervision of

Dr. RALLAPALLI SRINIVAS

Co-Supervisor

Prof. JOE MAGNER

BIRLA INSTITUTE OF TECHNOLOGY & SCIENCE

PILANI - 333 031 (RAJASTHAN), INDIA

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ABSTRACT

Water is inherently constituted and influences practically all the major systems across the globe involving environmental, biological, geological, economic, and social systems. Nevertheless, the importance of water has been continuously overlooked by contemporary civilization. As a result, we have reached a state where the rivers (one of the primary sources of blue water), amongst other ecosystems, are most threatened worldwide. The major causes of their impairment are agricultural runoff pollution, municipal and industrial wastewater, stormwater runoff, and atmospheric deposition. Consequently, human health, aquatic biodiversity, economics, etc. are vastly affected. However, in recent studies, pollution from agriculture is accepted as the leading cause of water pollution. Agricultural pollution is primarily furthered by agricultural runoff, i.e., the transport of nutrients, pesticides, and sediments from the agricultural fields to the waterbodies, poultry and livestock breeding, and aquaculture. While the pollution generated from the agricultural fields, influenced by natural and anthropogenic intercessions, contributes maximum agricultural non-point source (ANPS) pollution.

This issue has progressively gained attention amongst researchers, and diverse methods have been engendered for studying agricultural non-point source pollution. With chief approaches being field monitoring of agricultural non-point sources; and their estimation using modeling techniques. Of the two, modeling approaches involving physical-based models or empirical methods are believed to be more effective and are commonly used for evaluating agricultural pollution loads. Soil and water assessment tool (SWAT) and Hydrologic simulation program-Fortran (HSPF) are examples of two robust models which have been extensively used for quantifying the ANPS pollution, assessing their impact on the water quality of riverine systems, and evaluating the efficacy of various conservation practices (CPs), also known as the best management practices (BMPs)*. BMPs are recognized as the most efficient way for reducing pollution, i.e., reducing nutrients, pesticides, and sediments in the runoff generated from agricultural fields. The research on effective and efficient allocation of these practices to the fields has been current for the past three decades. But very few lands on the planet ascribe to these conservation measures.

Further, in the Indian context, the situation is still precarious. The Ganga River, sheltering about half of the Indian population, is suffering from the acute problem of sewerage and industrial point source pollution. This overrides even the consideration of ANPS pollution

The terms CPs and BMPs have been interchangeably used in this thesis.

management, which is unjustifiable because of India's leading position in the agricultural domain, i.e., at par with nations like the US and China, which are immensely affected and have their ecosystems and water resources severely threatened. Thus, the present synthesis develops and suggests a range of decision-support frameworks with simultaneous consideration of hydrologic, economic, and agronomic factors alongside incorporating the local watershed stakeholders' preferences for promoting the field-scale acceptance of conservation solutions or BMPs. This thesis also establishes a common platform between watershed planners, government officials, and landowners for sharing their mutual knowledge base, opinions, and conflicts.

Contemporary technological advancements in the form of artificial Intelligence concepts like fuzzy set theory, heuristic search algorithms, remote sensing, geographical information system (GIS), watershed-scale modeling software, and their combinations, etc., primarily constitute the decision support frameworks developed in this research work. These novel approaches deliver cost-effective, sustainable solutions to landowners, watershed planners, and government officials by assessing the field-scale hydrological nutrient transfer processes and their sources. These frameworks provide systematic, effective, and pragmatic conservation solutions for instating sustainability in the land-agriculture-water nexus. The present study reviews the state-of-the-art practices in terms of the novel modeling techniques and best management practices being utilized in agriculturally intensive regions of the technologically developed and advanced nation, the United States, and fulfills the existing research gaps towards cost-effective, simple, and efficient field-scale implementation of conservation practices (CPs) in the Indian watersheds by suggesting novel techniques. Concurrently, India's one of the most agriculturally intensive lands draining into and bounded by the impaired stretches of iconic Ganga and Yamuna has been taken as a testing ground for developing, demonstrating, and validating the selected proposed models.

At the outset, in Chapter 4, the crop rotation-based sustainable agriculture planning framework was developed that considers the preservation of soil fertility, maximizes the farmers', and minimizes the irrigation water requirement. This was achieved by integrating geoinformatics, stochastic optimization, and constraint optimization techniques, and sustainable crop rotation patterns considering seven major crops for the selected area were engendered. Chapter 5 offers a prompt and effective agricultural pollution management scheme/framework by integrating the farmers' conservation preferences. The framework is

**The terms CPs and BMPs have been interchangeably used in this thesis.*

demonstrated for four targeted watersheds' (31 subbasins corresponding to 4 subdistricts) based BMPs using graph network-based optimization platform into a field calibrated and validated watershed hydrological model. Chapter 6 further fostered sustainable agriculture by systematically identifying key challenges that prevent in-field implementation of precision agriculture practices. For this, the failure probabilities of the 21 fundamental events or challenges in precision agriculture implementation were deduced using the fuzzy fault tree analysis. Next, in Chapter 7, the efficacy of HSPF-based improved decision support tool, Scenario Application Manager (SAM), in rendering cost-effective coalescence of CPs to meet the total maximum daily loads (TMDL) for an agriculture-intensive watershed in the USA, from the viewpoint of learning from their cutting-edge technology/BMPs, was examined. The chapter optimized the targeting of seven CPs for reducing sediment and phosphorus pollution loads in order to achieve the respective Total Maximum Daily Loads (TMDL) limits set forth by the Minnesota Pollution Control Agency (MPCA). The applicability of the SAM model for Muzaffarnagar (a district Uttar Pradesh, India) has also been discussed therewith. Finally, in Chapter 8, the water quality degradation in the Mississippi River (in the USA) caused by the land-use change from internally drained prairie wetland to the intensively managed corn-soybean production system in north-central Iowa and south-central Minnesota was reviewed and examined. In this chapter, four perennial options were reviewed and targeted based on the parameters such as cost-effectiveness, level of acceptance using a fuzzy logic-based approach. Consequently, how these perennial options could be translated to the Indian context were deliberated.

Conclusively, the present research serves to deliver the vital need for the riverine ecosystem by strategically furthering the novel approaches for fulfilling the research gaps that prevent the on-ground implementation of conservation solutions.

**The terms CPs and BMPs have been interchangeably used in this thesis.*

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LIST OF ABBREVIATIONS

ABBREVIATIONS	**FULL FORM**
ACI	Acceptance with conflicts and incentivization may be required
ACPF	Agricultural Conservation Planning Framework
AGNPS	AGricultural Non-Point Source Pollution Model
AHP	Analytical Hierarchy Process
AnnAGNPS	Annualized AGricultural Non-Point Source Pollution Model
ANPS	Agricultural non-point source
BE	Basic Event
BMPs	Best Management Practices
CCP	Conservation Cover Perennials
CCR	Conservation Crop Rotation
CE	Cost Effectiveness
CI	Conservation Identity
CNHM	Commonly perceived as nuisance and hard to maintain
CO	Constraint Optimization
COD	Chemical Oxygen Demand
CPs	Conservation Practices
CPCB	Central Pollution Control Board
CR	Consistency Ratio
CWC	Central Water Commission
CWA	Clean Water Act
CGF	Clean Ganga Fund
DM	Decision Maker
DMLT	Des Moines lobe till
DNB	Denitrification and Biofiltration
DS	Depression Storage
EC	Electrical Conductivity
EPIC-APEX	Environmental Policy Integrated Climate - Agricultural Policy/Environmental eXtender
FAHP	Fuzzy Analytical Hierarchy Process

ABBREVIATIONS	FULL FORM
FAO	Food and Agriculture Organization
FFTA	Fuzzy Fault Tree Analysis
FIS	Fuzzy Inference System
FLM	Functional Land Management
FPS	Fuzzy Probability Score
FRNR	Flow reduction and Nitrogen removal
FS	Filter Strips
FTA	Fault Tree Analysis
GAP	Ganga Action Plan
GDP	Gross Domestic Product
GIS	Geographic Information Systems
GPS	Global Positioning System
HEC-HMS	Hydrologic Engineering Center - Hydrologic Modeling System
HMS	Hydrologic Modeling System
HRUs	Hydrologic Response Unit
HSPF	Hydrological Simulation Program - FORTRAN
ICAR	Indian Council of Agricultural Research
IMD	India Meteorological Department
ISRIC	International Soil Reference and Information Centre
IWR	Irrigation Water Requirements
K	Potassium
LMLI	Little maintenance and low initial cost
LOA	Level of Acceptance
LULC	Land use land cover
MIR	Maximization of Income Return
MIWR	Minimization of Irrigation water requirement
MoM	Methods of Moments
MPCA	Minnesota Pollution Control Agency
N	Nitrogen
NDVI	Normalized Difference Vegetation Index
NH_3N	Ammonical Nitrogen

ABBREVIATIONS	FULL FORM
NIR	Net Income Return
NMCG	National Mission for Clean Ganga
NMMI	Nutrient Management and Manure Incorporation
NO_3	Nitrate Nitrogen
NPS	Non-point source
NRCS	Natural Resources Conservation Service
NRP	Nitrate Reduction Potential
OC	Organic Carbon
P	Phosphorus
PATs	Precision Agriculture Techniques
PdT	Pomme de Terre
PTMapp	Prioritize-Target-and Measure Application
RB	Riparian Buffers
ROI	Return On Investment
RI	Random Consistency Index
RRSP	Runoff reduction and sediment pollution removal
RT	Reduced Tillage
RUSLE	Revised Universal Soil Loss Equation
S1	Highly Suitable
S2	Moderately Suitable
S3	Marginally Suitable
SAM	Scenario Application Manager
SB	Saturated Buffers
SFMC	Support from farmers, drainage managers, and water conservation professionals
SPARROW	SPAtially Referenced Regressions On Watershed attributes
SPC	Stochastic Pairwise Comparison
SRNR	Slowdown of runoff and Nitrogen Removal
STEPL	Spreadsheet tool for estimating pollutant load
SWAT	Soil and Water Assessment Tool

ABBREVIATIONS	**FULL FORM**
SWMM	Storm Water Management Model
TE	Top Event
TMDL	Total Maximum Daily Load
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TSD	Two-Stage Ditch
TSS	Total Suspended Solids
TP	Total Phosphorous
USA	United States of America
USDA	United States Department of Agriculture
USDA-ARS	United States Department of Agriculture - Agricultural Research Service
USEPA	United States Environmental Protection Agency
WARMF	Watershed Analysis Risk Management Framework
WASCOB	Water and Sediment COntrol Basin
WQI	Water Quality Improvement
Zn	Zinc

CHAPTER 1

INTRODUCTION

1.1 Background

Water is uniquely associated with the overall well-being and economic development of individuals, society, and even nations. Among other resources of water, river water is chief and fulfils the domestic, industrial, agricultural, and hydro-power generation requirements. The apparent increase in the living standards and development of human civilization in the form of rapid industrialization, excessive use of chemical fertilizers, pesticides, and land use change have impaired the river waters worldwide. Additionally, the increased consumption and overexploitation of water resources have led to a decline in water quantity causing river water contamination which is a chief socio-economic hurdle, especially in the countries like India, China, and Indonesia (Guru, 2011). The pollution sources could broadly be divided into two categories: point and non-point sources (NPS) of pollution. The point sources are concentrated and are discharged through a fixed stationary point. Municipal sewage water and industrial wastewater are two examples of point sources of pollution. In contrast, the non-point sources of pollution are decentralized and are intermittently discharged into the surface water bodies as soil loss, agricultural land runoff, and water discharged from rural dwellings. The random, abrupt, and complex nature of non-point source pollution renders their identification, control, and management greatly tedious. The relatively easier identification of the point source pollution has leveraged or attracted the research focus.

Consequently, effective point source pollution control has been observed in the past few decades. Conversely, over time, the negligence of the non-point sources of pollution has turned them into serious/primary sources of water pollution in many parts of the world. For instance, 60% of the US water pollution is contributed by non-point source pollution (Xie et al., 2022). More than 80% of nitrogen and 90% of phosphorus load is contributed by non-point source pollution in China (Wang et al., 2019a). The developed countries have put in great efforts to control NPS pollution like the US has implemented Clean Water Act and Watershed Prevention Approach, and the European Union’s Water Framework Directive and Drinking Water Directive. Also, China is considered to have paid maximum attention to NPS control than any other developing country (Lei et al., 2021; TMDL, 2017) by enforcing the many laws such as Water Pollution Control Law, and Yangtze River Protection Law, etc.

Non-point source pollution is derived or generated from on-land activities, urban runoff, agriculture, construction, etc. The unsustainable agricultural practices are progressively being realized as the leading source of non-point source pollution, causing the deterioration of river waters worldwide (Duda, 1993; Lam et al., 2010; Scavia et al., 2016; Wang et al., 2019b). The excessive discharge of phosphorus (P) and nitrogen (N) into the lake, rivers, estuaries, and oceans from the agricultural fields, in addition to the siltation furthered by the erosion in agricultural fields, etc., are the typical causes of degradation of surface waters (Carpenter et al., 1998; Srinivas et al., 2020). The aquatic plants and animals require only a small amount of N and P for their development and metabolism—the excess N and P trigger eutrophication augmenting the algae and aquatic weeds advance, which in turn depletes the available dissolved oxygen and destroys the aquatic biodiversity, i.e., killing of fish, loss of aquaculture habitat. Moreover, algal growth is also pernicious for livestock, humans, and several other organisms by dint of its setting aside the impaired water for drinking, industrial, agricultural, and fish culture use.

The Ganga River, sheltering about half of the Indian population (more than 600 million), supporting 40% of countries Gross Domestic Product, and even being greatly revered for its spiritual heritage, is no exception to this universal plight (TWB, 2015). The Indian government has also taken various initiatives for Ganga rejuvenation, which includes the Ganga Action Plan (GAP), the coalition with eminent educational institutions and industries, and the establishment of the National Ganga River Basin Authority. However, these initiatives were limited, focusing primarily on the abatement of sewerage pollution (NMCG, 2020). The contemporary Namami Gange initiative by the government of India is an integrated and comprehensive program targeting a holistic river water restoration scheme through the implementation of four fundamental pillars (i.e., Nirmal, Aviral, Jan, and Gyan Ganga; (NMCG, 2020)). The initiative also exclusively enjoins private sector involvement by facilitating Clean Ganga Fund and cooperation from the state-level authorities (Ahmed et al., 2022; Chaudhary and Walker, 2019). However, agricultural NPS pollution has still been given a little focus, with a primary focus on promoting organic farming, improving irrigation water efficiency, etc., which are long-term plans and are hardly sufficient for prompt redressal of the emergence.

India, like US and China, reckons a leading position in food production and fertilizer consumption (Investopedia, 2023; Statista, 2019), which supports or underpins a belief that "the Indian water bodies must also have been stressed similarly, which are presently getting overwhelmed by the high-intensity pollution caused by the sewerage and industries." In fact, the apparent sewage nutrient pollution resulting in major algal blooms in the tributaries of the Ganges (Bowes et al., 2020; Pandey and Yadav, 2017), could have a significant contribution from the agricultural NPS pollution. Since the early 1980s, especially in the past two decades, US has attained achievements in its research on agricultural non-point source (ANPS) pollution control (Xu, 2014). The US government has established effective legislative frameworks like Clean Water Act (CWA) that have positively directed the NPS management strategies. Other voluntary conservation initiatives by the US government, such as Conservation Reserve Program (CRP) and the Environmental Quality Incentives Program (EQIP), have enhanced and encouraged farmers'/landowners' environmental consciousness through various financial supporting schemes. The regulation of ANPS pollution demands voluntary participation and employment of conservation solutions, also known as Best Management Practices (BMPs). US government pioneered the use of BMPs in the 1980s, and extensive research for their on-ground adoption is current. In the Indian context, there is a dearth of knowledge regarding estimating the extent of NPS pollution and the subsequent damage rooted in a lack of research in this direction.

Additionally, the ANPS pollution problem could be associated with the lack of related knowledge on ANPS pollution, i.e., the information of the sources contributing ANPS pollution, their transportation to the river waters and the associated physical/chemical processes, etc. Other prominent factors could also include the lack of strategies, policy frameworks, methods, and technical dissemination methods for relating NPS pollution information to the farmers. Thus, the prompt and proactive measures incorporating the state-of-the-art ANPS pollution abatement practices followed by advanced nations like the USA are prudent. Elsewise, the progressively intensifying water pollution in Indian rivers might turn the situation irreversible.

BMPs are proven to be the most efficient ways for achieving pollution reduction (Wang et al., 2019) or improvement of ground and surface water quality (by achieving reduction in Nitrogen, Phosphorus, and Sediment loads in excess runoff generated from agricultural fields) (Opoku-Kwanowaa et al., 2020). A BMP could be a practice or a set of practices, which are efficient and pragmatic in reducing the NPS pollution for attaining the water quality goals (Jain and Singh, 2019). Some of the areas for BMPs application in agricultural fields are cropping practices, tillage, improvement in application of pesticides and fertilizers, structural practices to reduce runoff, and so on. BMPs can effectively be categorized into

Structural and Non-Structural BMPs. Where structural BMPs involves erection of some structure like grass swales, contour farming, etc., while non-structural BMPs are practices dealing with entities like irrigation, crop, and weed management etc. These practices are in the research from about past three decades, however, only a few lands on earth are ascribing to these practices (Rodrigues et al., 2021). This is true because of many limitations, the resident nutrients in the agricultural land-soil system delay the immediate load reduction through BMPs, which poses a great challenge to fixing a time period for achieving pollution reduction targets and evaluating the particular BMP. Additionally, the cost and time requirements in regular monitoring of these practices makes performance, effectiveness, and assessment correctness evaluation of practices difficult. Sometimes the set of BMPs selected or centred around targeting conditions (e.g., land, soil, crop) and achieving target reductions, might not be the most cost-efficient selection. Also, many a times, the consideration of spatial interactions of BMPs is not given due attention. Hence, there must be cost-efficient evaluation and implementation scheme for BMPs that can, consequently, help gaining confidence among the watershed managers and fulfil the goals towards achieving optimal TMDL targets.

Watershed modelling tools have found to be useful for carrying out watershed-scale water quality assessment and water pollution control (Fu et al., 2020; Li et al., 2022). These models could be used to evaluate/quantify the sediment and nutrient runoff load originated from the non-point sources before and after implementation of the BMPs in a watershed. These watershed modelling tools take inputs from the multiple subdomains of soils, climate, land use/land cover, topography over varied spatial and temporal scales. The Soil and Water Assessment Tool (SWAT) is one such tool that has been used in this research for modeling the study watershed. Owing to its vast library of simulation components/modules, SWAT can systematically simulate the impact of agricultural activities as well as the management practices over long periods on the water quality downstream, taking into account the variations of soil, land use, fertilizer, and pesticides inputs to agricultural fields and practices. In United States, the spreadsheet tool for estimating pollutant load model for recording BMP on-site load reduction has been inconsistent. Therefore, a watershed modelling approach could be useful in evaluating the impact of BMPs on the sediment and nutrient loads, allocation of BMPs, critical source pollution area estimation, etc.

Further, geographic information system (GIS) and remote sensing are found useful tools for providing input for watershed models. The combination of these two tools can be used to capture and process raw data and provide as input for the watershed models. Also, the models' output can be well presented (graphically or in map form) with the help of GIS (Quinn et al., 2019). GIS is a framework which displays and analyzes geographic data (USGS, 2021). GIS's use is not only in mapping and managing data, but it also assists by performing advanced and complex analysis on spatial data by employing array of mathematical tools and models. Another one important feature of GIS is its overlay analysis, where GIS engenders a new data layer incorporating the respective features of existing data layers. On the other hand, remote sensing is a vital tool for capturing and monitoring of soil resource, land use land cover, and geomorphological, precipitation information with large spatial coverage and high temporal resolution (Sheffield et al., 2018). The other helpful aspects of remote sensing are like use of thermal band satellite data which can give estimate of surface temperatures, estimation of sediments, nutrients, metals etc. by optical reflection on water surface or by surrogate indicators (Quinn et al., 2019). Thus, remote sensing finds its use in watershed modelling in the form of data collection via spectral imagery at different resolutions and bands. Data regarding soils, cropping patterns (land use patterns), water quality parameters, meteorological information etc. can also be collected from sources other than those providing remote sensing imagery like from the respective governmental or private organizations and departments: India Meteorological Department (IMD), Indian Council of Agricultural Research (ICAR), etc.

The random nature of meteorological data like temperature, precipitation and the computational processes in the hydrologic models involves uncertainties (Rehana et al., 2009; Srinivas and Singh, 2018; Xie and Lian, 2013; Zhang et al., 2014). Thus, the fuzzy logic techniques can be successfully implemented to tackle the uncertainties associated with the retrieved data information (Celik et al., 2009). Other Artificial Intelligence techniques such as genetic algorithms because of their ability to replicate the system behaviour without having explicit understanding of the physical system involved are also efficient tools for data forecasting and prediction. Thus, the run-off prediction, climatic processes and land uses patterns can be well forecasted using these models (Mariganti et al., 2009; Noori and Kalin, 2015; Pradhan et al., 2019). Artificial Intelligence technology is now also emerging in agricultural field, it is particularly advantageous and helpful in precision agriculture (Talaviya et al., 2020).

The present research is focussed towards utilising the contemporary technological advancement in form of artificial intelligence concepts, remote sensing, software compatible to process geographic and spatial data, their combination, and the overseas experience (from USA) for developing effective and sustainable agricultural conservation solutions and limiting impairments of waterbodies contributed by the ANPS pollution. Further, the effort of suggesting conservation solutions will only be fruitful if the suggested practices find their ways to the agricultural fields without any conflicts. These conflicts may arise from various limiting factors such as economic budgets, farmers disagreement, government support etc. These issues are, however, rooted in lack of knowledge on the part of farms and crunch of funds. The solution to this problem lies in, if there can be a common platform/interface for farmers/landowners, watershed planners, and governmental professionals where they can share their opinions, conflicts, and knowledgebase. Thus, the present research work is directed towards the development of decision support frameworks for effective watershed modelling incorporating considerations from environmental, economic, hydrologic, socio-economic, agronomic factors.

1.2 Major contributions and thesis outline

The major contributions to this thesis are summarized below:

1. Promoting crop rotation for sustainable agriculture

Chapter 4 proposes a sustainable framework for agricultural management for preserving soil fertility, maximizing agricultural profit, minimizing agricultural pollution, and water usage considering seven prominent crops in the Muzaffarnagar district, Uttar Pradesh (India). The use of technologies and machineries has tremendously increased producing more food than ever before. Since, the beginning of the 1960s it was becoming more and more evident that the escalation in food production is affecting the environment negatively in the form of soil health deterioration, and the raising issues for biodiversity protection. Gradually, over the decades, the environment consciousness gained momentum and the efforts to balance productivity and environmental health gave rise to the concept of sustainable agriculture. The proposed framework supplements the environmental consciousness while additionally considering the farmers' profit. The chapter offers a unique framework by suggesting sustainable crop rotation practices and ensures minimum irrigation water use and maximum farmer's profit. Using a systematic approach, comprising the use of geoinformatics, stochastic optimization, and other relevant datasets under the ArcGIS environment, crop-rotation patterns for each land parcel for the Muzaffarnagar were generated. The study highlighted that the systematic cultivation of sorghum, mustard, rice, wheat, sugarcane, potato, and maize could resolve the present concern of lowering water tables and overexploitation of land in the study area. Also, the inclusion of an interactive web-based dashboard in this study is valuable for promoting optimized crop rotation practices adoption among the farmers and could also serve as a guide for agricultural policy and planning for state-level/central governmental bodies.

2. Identification of precision agriculture practices implementation challenges

Chapter 5 furthers a farmer conservation consciousness driven rapid conservation practices adoption approach combining the traits of graph network-based optimization to enable selection of integrated and efficient conservation practices. The agricultural non-point source pollution is consistently exacerbating since the past few decades and has at present become a worldwide threat. This demands an immediate in-field implementation of the conservation practices for minimization of the ANPS pollution discharge into the natural water resources. Thus, this chapter developed a model that integrates the measure of farmers' conservation practices adoption and a novel graph network-based optimization into a robust watershed hydrology and BMP simulation model, SWAT. A one-to-one in-field famer questionnaire survey was conducted in the four major sub-districts (Shahpur, Morna, Khatauli, and Purkaji) of the study watershed to capture the farmers' conservation consciousness, age, education, and the prominent conservation practices prevalent in the study region. These responses engendering three possible BMP targeting scenarios together with the optimized and integrated BMPs (riparian buffer, nutrient management, cover crops, and conservation tillage) were integrated into SWAT model calibrated and validated for a time period of 2013 to 2020 using the monthly observed discharge and nitrate at the study watershed outlet. Based on the study results, the adoption of the combination of riparian buffer and conservation tillage in the subbasins related to Morna subdistrict was found out to be the most efficient for controlling agricultural nitrate pollution. Further, the chapter results systematically highlighted the importance of incorporation of farmer behavioural responses for immediate and effective targeting of the conservation practices to the agricultural watersheds.

3. Identification of precision agriculture practices implementation challenges

Chapter 6 develops a fuzzy fault tree analysis-based decision support framework to identify the challenges concerning on-ground implementation of precision agricultural practices. The conception that the soil and the water resources are inexhaustible or ample resources of supply has now been revised owing to the long-term anthropogenic impacts on these resources. However, precision agriculture techniques have been identified as solutions which can improve and refurbish these natural resources. The chapter employs expert elicitation and a fuzzy logic approach which incorporates the uncertainties into the data obtained from various stakeholders and determines the failure probability of the various challenges in precision agriculture implementation. The study classified the problems associated with the on-ground implementation of precision agriculture practices based on three farmer categories – innovators, early adopters, and late adopters and a case study for the Muzaffarnagar district was presented. Exploiting the weighted expert opinions/decisions on 24 basic events, the failure probability of the top event was assessed using fuzzy fault tree analysis. The results indicated that rigidity in adopting new technologies, cost of implementation, and implementation difficulties concerning the small land holdings are the major issues which prevents the field-scale adoption of precision agriculture practices. The analysis suggests that increased awareness and cost-effective technologies (e.g., sensors and global positioning systems) can enhance the farm-scale acceptance of precision agriculture techniques. The study findings could be extremely helpful for the researchers, farmers, and local community and could serve as a comprehensive guide for bridging the gap between precision technologies and their on-ground acceptance.

4. Managing nutrient loads from cropland dominated land areas in USA

Chapter 7&8 discusses the advances in hypoxic area in the Gulf of Mexico and suggests two novel, simple, and effective approaches to manage the nutrient loadings transport from the intensively drained cropland units in Mississippi River Watershed. The hypoxic zone in the Gulf of Mexico, primarily furthered by the excess of nutrients, is increasing by an average of four thousand square miles every summer. The landscape conversions, predominantly the substitution of freshwater wetlands for agricultural lands, is one of the major contributing factors responsible for this upsurge in hypoxic space. The strategical field-scale implementation of conservation practices for reducing nutrient export has been recognized as a promising approach for curbing such unintended episodes. These chapters examine the efficacy and suitability of two simplified approaches for recommending the conservation practices, viz., fuzzy logic-based and HSPF-based decision support. The former technique was examined for Des Moines lobe till (DMLT) watershed, and four perennial plants options were recommended for the designed scenarios based on the four parameters: cost effectiveness, nitrate reduction potential, water quality improvement, and level of acceptance.

On the other hand, using Scenario Application Manager (SAM), seven conservation practices were evaluated for the Pomme de Terre Watershed. SAM utilized the HSPF's output for developing optimized design scenarios for achieving desired TMDL targets cost-effectively. The results suggested that the reduced tillage and the filter strips are the two most cost-effective practices in attaining TMDL goals for the Dry Wood Creek watershed. And no combination of conservation practices could achieve TMDL goals unless there is a minimum of 83.7% of participation of the farmers. While the fuzzy logic-based approach delivers promising decision support when there is a lack of quantitative records and ambiguity in relation to the performance of the conservation practices.

1.3 Organization of the Research

This section provides a concise and holistic description of the thesis as follows:

Chapter 1 introduces the importance, present situation, major causes, and repercussions of the river water contamination worldwide followed by various practices, techniques which could be used in developing decision support models/tools for the effective control of non-point source pollution in the river waters. Additionally, the objectives, scope, and organization of the the present research have also been intimated. In the 2nd chapter, various conservation practices, models, and technologies related to NPS modelling at the watershed-scale are discussed and conservation practices or BMPs under the source, process, and end control approaches of ANPS pollution management are also critiqued. Consequently, the research gaps, objective, and scope were discussed in the 3rd chapter.

The 4rth chapter develops a framework for source control of the ANPS that optimizes sustainable crop rotation practices and, thereby, minimizes the use of chemical fertilizers and pesticide runoff from the agricultural fields as well as the irrigation water required, and maximizes the farmers' profit. Chapter 5 facilitates the immediate acceptance or adoption of optimized and integrated conservation practices in the agricultural watersheds by considering the farmers' behavioural responses and integrating graph-network based optimization to a systematic hydrological watershed model developed using SWAT. Chapter 6 fortifies sustainability by complementing conservation solutions with precision agriculture techniques. Thus, a systematic fuzzy-fault tree decision support system pivoted on the farmer's category (i.e., innovators, early adopters, and late adopters) is developed to identify the major challenges that checks the on-ground implementation of precision agriculture techniques.

Chapters 7 & 8 discuss two simple and effective approaches, i.e., a fuzzy-based and HSPF-SAM based decision support for targeting the conservation solutions. Additionally, the applicability of these models and the targeted BMPs (practiced in the USA) to the Indian context have also been reasoned.

The conclusions and the major findings are presented in the 9th chapter of this synthesis. The present research delivers innovative and promising solutions in various frameworks/models for addressing agricultural non-point sources for the agriculturally dominated regions in the Indo-Gangetic plains and the associated limitations/assumptions are discussed in the respective chapters and wherever necessary. Lastly, the key salient features, areas for future works, and concluding remarks have also been discussed in the separate sections in chapter 9.

1.4 Bibliographical note

Parts of Chapter 1, 2, 4, and 6 appear in the following journal paper:

Aggarwal, S., Srinivas, R., Puppala, H., and Magner, J. 2022. Integrated decision support for promoting crop rotation based sustainable agricultural management using geoinformatics and stochastic optimization. *Computers and Electronics in Agriculture* 200, p. 107213.

Parts of Chapter 1, 2, and, 5 appear in the following submitted paper:

Aggarwal, S., Srinivas, R., Magner, J., and Singh, A.P. Farmer adoption-based rapid networking for targeting optimal agro-conservation practices. *Environmental Modelling & Software (Under Review)*

Parts of Chapter 1, 2, and 7 appear in the following submitted paper:

Aggarwal, S., Rallapalli, S., Nithyasree, T., Sabarish, B.A., Drewitz, M. and Magner, J. Decision support for cost-effective coalescence of agricultural conservation practices to meet total maximum daily loads in Pomme de Terre watershed. *Journal of Hydrology (Under Review)*

Parts of Chapter 1, 2, and 8 appear in the following journal paper:

Aggarwal, S., Magner, J., Srinivas, R. and Sajith, G. 2022. Managing nitrate-nitrogen in the intensively drained upper Mississippi River Basin, USA under uncertainty: a perennial path forward. *Environmental Monitoring and Assessment* 194(10).

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The sustainable management and strategic planning of rivers are widely regarded as crucial objectives, given their significant contributions to economic and social growth. The river's freshwater offers a range of benefits to living organisms, including power generation, irrigation, domestic consumption, industrial activities, and recreational opportunities (Tickner et al., 2017). It is noteworthy that several of the world's major rivers, such as the Mississippi River in the United States, Sarno in Italy, the Yellow River in China, and the Ganges in India, have become significantly contaminated because of multifaceted projects, industrial activities, agricultural discharges, and domestic wastewater (Schneider, 2016). This suggests that while technological progress has enhanced living standards, it has also caused substantial damage to several prominent river systems worldwide. As a result, policymakers and experts face a daunting challenge in ensuring the sustainability of these ecosystems.

The river Ganga, which spans 2,525 kilometres and has a basin area of approximately 1,080,000 square kilometres, is the most extensive River Basin in India. It encompasses an area of more than 26% and sustains a population of more than 40%. The river Ganga, which is considered to be the birthplace of Indian civilization, is currently facing significant challenges. This situation serves as a representation of the inadequate governance within the contemporary Indian State. The Ganges River, which holds significant national and cultural significance, has experienced a decline in quality since the mid-1800s due to the implementation of extensive canal systems for water abstraction. This has become increasingly complex and intensified in recent decades due to various factors such as rapid population growth, changes in agricultural practices, industrialization, urbanisation, and alterations in land use. The Ganga River Basin is a region of concentrated agricultural activities due to its fertile nature. During the period following the Green Revolution, agricultural chemicals such as fertilizers and pesticides were readily introduced into the river system. The confluence of various sources of pollution such as solid waste dumping sites, open defecation, incomplete combustion of corpses and animal remains, laundry areas, cattle bathing, and mass religious offerings, constitute non-measurable and non-point sources of pollution.

Non-point sources of pollution have been largely overlooked due to its complex generation and transportation. In response to the increasing threat of pollution, the Indian government initiated the Ganga Action Plan (GAP) in 1985. The National Ganga River Basin Authority was subsequently established in 1986 to serve as a coordinating, monitoring, planning, and financing entity aimed at enhancing the joint efforts of the Central and State Governments. The initiation of GAP II occurred in the year 1993. In 1995, the plan underwent a name change to the National River Conservation Plan and was expanded to encompass a comprehensive approach towards mitigating pollution levels in other segments of major rivers that had been identified as polluted. The Ganga was officially designated as the National River of India in the year 2008. The year 2011 marked the establishment of the National Mission for Clean Ganga (NMCG) which was designated as the implementation arm of the National Ganga River Basin Authority. According to official government records, by the year 2014, completion rates for GAP-I and GAP-II schemes were reported to be 99% and over 85%, respectively. Despite of various intervention and sustained efforts spanning three decades, no significant progress was made, except for the closure of certain polluting facilities (The Statesman, 2017).

Further, the Ministry of Environment and Forests entrusted a consortium comprising seven Indian Institutes of Technology with the task of formulating the Ganga River Basin Environment Management Plan. Under this plan, numerous literatures were published to provide strategic guidance, informational resources, methodological frameworks, analytical insights, and recommendations. In May 2015, under the direction of the Prime Minister, the 'Namami Gange' Programme was approved by the Union Cabinet aiming at the comprehensive restoration and preservation of the river, with an allocated budget of Rs. 20,000 crores until 2020. The inadequate planning, research, and failure to anticipate the future needs have resulted in the ineffective management of point source pollution and nonpoint source pollution, over the past three decades. Currently, the level of pollution in the Ganga River exceeds the permissible limits for many pollution parameters for the different stretches. Despite significant financial investment, the goal of achieving integrated river basin management has yet to be achieved.

Both point and non-point sources of pollution have serious effects on the river ecosystem, modelling non-point pollution has proven to be challenge for the researchers and policymakers (Srinivas et al., 2020). In order to estimate the NPS loads and to enhance the decision-making, a range of techniques have been employed in recent years. These include field monitoring and model prediction, which are considered the two primary approaches (Ouyang et al., 2017; Xue et al., 2022). The methods used for field monitoring are often associated with significant expenditures of time, finances, and labour. Consequently, the availability of monitored data may be limited, rendering these methods ineffective and constrained in their application at a larger scale. The use of modelling techniques, such as empirical evaluation methods and physical-based models, has been established as a prevalent and efficacious tool for assessing NPS pollution loads, as evidenced by the, studies conducted by Xue et al. (2022) and Yang et al. (2016). Thus, the subsequent section reviews the various techniques, models, and practices from the past studies and identifies the plausible research gaps in effective handling of the non-point source pollution.

2.2 Conservation practices or best management practices

The ANPS pollution affects the soil, surface waters, ground waters, and living beings. The degradation of the groundwater quality directly affects the drinking water such as accumulation of nitrite in the groundwater (Münzel et al., 2023; Wang et al., 2015a). Besides, the contaminated drinking water bearing carcinogens and other toxic elements released by fertilizers, pesticides, fungicides and herbicides, can cause liver related and other serious diseases, or even mortality (Opoku-Kwanowaa et al., 2020). In essence, the chemicals drained from the agricultural fields affect both abiotic and biotic species and a considerable nitrogen in the form of oxides is released into the atmosphere, furthering climate change and global warming (Motesharezadeh et al., 2017; Wang et al., 2015a; Wang et al., 2015b). Reducing agricultural non-point source pollution is therefore an essential subject of concern to safeguard individuals' health, effectively manage eutrophication in lakes and rivers, and to safeguard the water environment. The quantification and diversion of nonpoint sources of pollution is challenging. However, the solution lies in the adoption of practices that can effectively curtail the generation of such pollution. Best Management Practices (BMPs) are a set of acceptable practices that can be implemented to preserve water quality and promote soil conservation.

There are several BMPs that can be implemented for attaining nonpoint source pollution reduction. Agricultural activities such as tillage, cropping practices, cropland conversion, improved ways of application of fertilizers and pesticides, and structural measures aimed at controlling erosion, nutrients among others are the areas where BMPs could be adopted.

Broadly, the BMPs could be categorized into structural and non-structural BMPs. Structural BMPs pertain to techniques that comprise the erection or establishment of a physical infrastructure to mitigate pollution. In contrast, non-structural best management practices do not necessitate any particular construction or development and takes effective measures to mitigate the pollution at source (Jain and Singh, 2019). Following is a generic example of a BMP with focus on its application, this is meant for elucidating the concept of BMPs using a simplified scenario.

2.2.1 *Simplified Filter Strip Scenario and its Application*

Best Management Practices, or BMPs, are methods and approaches used to mitigate the adverse effects that different activities, especially those related to agriculture, have on the environment. Using filter strips, which are deliberately positioned vegetated areas designed to catch and filter runoff water before it enters water bodies, is one particular BMP. To better understand BMPs, a simplified example using filter strips and their role in reducing non-point source pollution in agriculture is discussed as follows:

Let us consider a conventional farming area where farmers cultivate crops. During rainfall or irrigation, field runoff carries sediment, nutrients (such as nitrogen and phosphorus), pesticides, and other pollutants. When runoff water flows towards the filter strip, the vegetation slows down the water, allowing particles like sediment to settle. The roots of the plants in the filter strip help absorb and filter out nutrients and pesticides present in the runoff (Fig. 2.1). In addition, the revival of the habitat for beneficial microorganisms helps in further breaking down the pollutants. The following steps set forth the guidelines for the application of filter strips,

- Identification of vulnerable areas where runoff, preferably sheet flow, is likely to occur and cause pollution. Slopes (less than 5%), proximity to water bodies, or locations with historically high runoff include typical parameter for vulnerable area identification.
- Strategic installation of filter strips, typically composed of grasses or other vegetation, along the edges of fields or between fields and water bodies (with minimum 25 ft width), thus acting as buffer zones.

- Selection of vegetation in the filter strip like native grasses and plants with deep roots. This enhances the stability and provides better filtration.
- Regular maintenance of filter strips such as periodic mowing, replanting, etc.

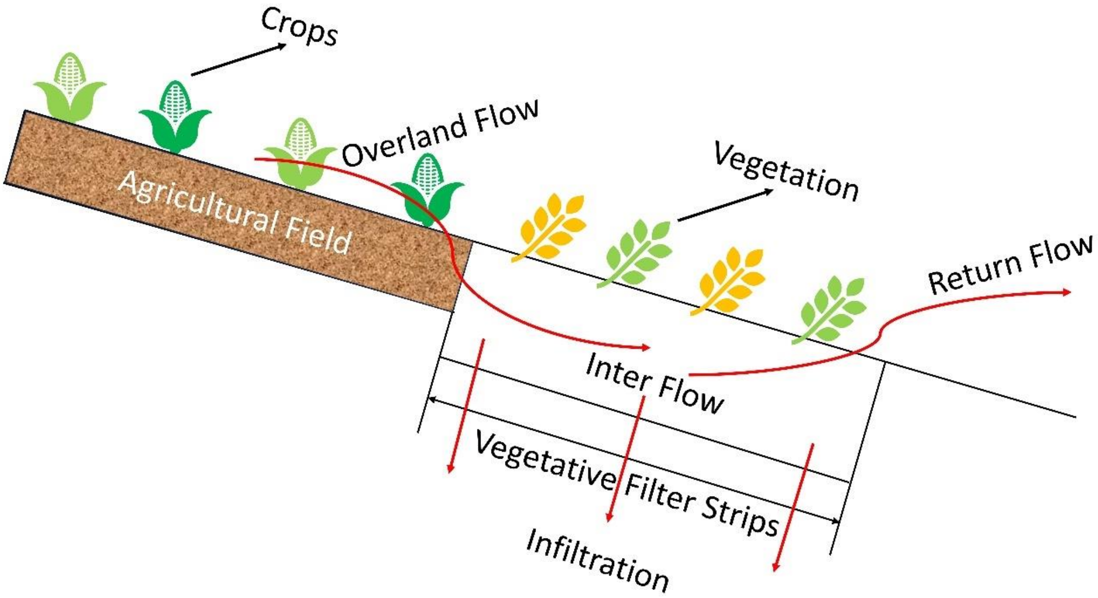


Fig. 2.1 Filter Strip (BMP) process.

From the perspective of sequential/progressive control of the agricultural runoff pollution, these BMPs could alternatively be classified into three primary measures of control, namely source control, process control, and the end treatment. Source control techniques, such as conservation tillage, fertilization management, and effective irrigation, have been found to successfully minimize the application of N and P and reduce leaching. The objective of process control is to mitigate the presence of contaminants in agricultural runoffs while these transport from the field (origin) to the receiving water bodies (destination). If the concentration of pollutants in the water does not decrease to a safe level, the final option is to implement end treatment measures to prevent harm to the receiving water. Following sections discusses the widely used technologies in addition to other potential alternatives (Peigné et al., 2007; Wu et al., 2013; Xia et al., 2020).

2.2.2 Best management practices for source control

Agricultural runoff contains dissolved pesticides, nutrients, and sediments that result in several issues, such as nitrogen loss, soil erosion, etc. For instance, a large amount of water is needed to grow rice, a staple grain for more than 25% of the world's population, which results in significant agricultural runoff. The dissolved nutrients and sediments provide a significant amount of pollution to the nearby waters. Instead of treating pollutants once they have gotten into the environment, source control technologies work to avoid or minimize the quantity of pollutants from getting into the agricultural systems.

2.2.2.1 Crop Rotation Practices

Crop rotation refers to the agricultural technique of cultivating crops in a specific order on a given field. There are multiple advantages associated with soil and crop systems. The advantageous outcomes of this approach encompass a reduction in the occurrence of weeds, insects, and plant diseases, alongside enhancements in the physical, chemical, and biological characteristics of the soil. Enhancements in the physical characteristics of soil involve an increase in water retention etc. and the biological characteristics of soil involve an upsurge in the organic matter replenishing the soil's N and carbon content (Asseng et al., 2014; Neupane et al., 2021). The suitability of crop rotation practices is contingent upon specific environmental and soil conditions, and therefore, cannot be universally applied across different locations. For example, biannual corn–soybean crop rotation in the Midwest United States is a dominant crop rotation practice, while in Asia, rotation of rice-wheat is the most prevalent (Alhameid et al., 2017).

Past research works analyzed the crop rotation planning (Alotaibi et al., 2021), where crop rotation decisions have been primarily dealt as a static concept and identified the need to model these decisions as dynamic problems (Dury et al., 2012). Ridier et al. (2016) built a dynamic stochastic model to aid crop rotation planning, keeping maximization of income over the planning period as an objective with simultaneous consideration of crop yield and market risks. Li et al. (2015) proposed a heuristic algorithm for optimal crop rotation scheduling to maximize profits for smallholder farmers and minimize the profit difference between the farmers. Fikry et al. (2021) proposed a strategic crop rotation planning model that analyzed operational and agronomic constraints to attain sustainable farming. Dos Santos et al. (2011) suggested and analyzed a binary optimization model disintegrated using Danzig-Wolfe decomposition and a heuristic based on column generation to identify a crop rotation schedule while maximizing the plot occupation subjected to adjacency and succession constraints. Further, a crop rotation model, CropRota, is presented by (Schönhart et al., 2011), which integrates observed land-use data and agronomic criteria for maximizing the agronomic value overall rotations by assigning discrete crops to a single or multiple crop rotation. Dupuis et al. (2022) presented a six-step methodology using Markov chains to predict N most likely crops for year n + 1. Similarly, many mathematical or computational models have been proposed for crop rotation planning problems (Alotaibi et al., 2021; Dos Santos et al., 2015; Capitanescu et al., 2017). Despite the various agronomic, production, financial, and market constraints and rules applied by these models, they do not account for the unique land potentials and specific deployment of cropping patterns to fields. Additionally, there is a lack of framework for the direct implementation of cropping plan recommendations in the field. Thus, the 4rth chapter develops a modelling framework which considers agronomic, economic, and ecological factors and provides a sustainable crop rotation planning framework.

2.2.2.2 Nutrient management and precision agriculture

Nutrient management is the management of nutrients to optimize the yield with simultaneous minimization of negative impacts on the environment. This involves management of fertilizers, manure, and other organic and inorganic amendments in order to deliver adequate amounts of nutrients such as nitrogen, phosphorus, and potassium, as well as secondary and micronutrients to the crops. Thus, avoiding nutrient loss and environmental contamination. The efficient implementation of this practice can help maintain soil fertility, improve crop productivity, reduce nutrient runoff, and protect water quality. Different crops have different N or P use efficiencies, like, maize, wheat, and rice are 37%, 18%, and 31%, N-fertilizer efficiency, respectively. The excess N and P, carried away by the surface runoff, find their way to the lakes and rivers. There are various methodologies which could be adopted for practicing fertilization management. The major practices include deep placement of fertilizers to lower the risk of discharging N into a body of water (Xia et al., 2020), controlled-release of fertilizer that can lead to slow release of N and P to be adapted to the rate of crop growth while improving nutrient utilization efficiency (Irfan et al., 2018), and Optimization of fertilizer timing and application rate is also important variables to control nutrient loss (Hua et al., 2017). The researchers in the past have found that band and hole placement of the fertilizers can substantially reduce the N and P loss as they minimize the microorganisms soil contact and inhibits the nitrification process. The band and hole placement practices have been found to reduce 60% and 70% of N loss respectively and 40% and 50% of the P loss respectively (Liao et al., 2017; Ye, 2016). While the controlled release of fertilizers containing P have found to lower the P loss by 62% for paddy and 33% for the corn crops (Kun, 2012). Similarly, Tan et al. (2013) studied the application of fertilizer management for the wheat-maize cropping system and reported that reduction in the N concentration in the runoff is best achieved by the controlled release of N fertilizer. In a recent study, Chen et al. (2020) summarized the mechanisms, methods, and application of sustainable chemical, coating, and chelation alterations for a lignin-based control release fertilizer production.

Precision agriculture, utilizing new technologies such as sensors, GIS, geo-graphic positioning systems, and other advanced techniques, targets to amend agricultural inputs both at spatial and temporal levels for enhancing production, profit, and environmental benefits. Past studies have shown that the season and site subjective calibrations of the agricultural inputs considering variable climate and yield potential enhances fertilizer use efficiency (up to 368%) in comparison to conventional agricultural practices. Radočaj et al. (2023) highlights that US, India and China are prominent research centres in the field of precision agriculture. In USA, precision agriculture has been embraced by many farmers as a way to increase efficiency and productivity (Fairbairn and Kish, 2022). Recently, the implementation rate of autonomous guidance technology has reached 60–80% in US (Erickson and Widmar, 2015; Miller et al., 2017). While yield monitoring technology and variable rate technology predominated before, autonomic control systems and auto guidance systems gained more traction in the last ten years (Say et al., 2018). In China and India, precision agriculture is also likely to be growing, as these countries look for ways to improve the efficiency of their agricultural industries and meet the increasing demand for food (Arrubla-Hoyos et al., 2022). India is one of the biggest exporters of food grains, thus researchers are clamouring for better methods to increase production (Chandio et al., 2022; Sengupta, 2022). Precision technologies like wireless sensor networks, general packet radio service, global positioning system, remote sensing, and Geographic Information Systems (GIS) are all in various stages of development in India (Ojha et al., 2015). China is actively engaged in the process of agricultural modernization to provide food security for its 1.4 billion population. The decrease in agricultural inputs like pesticides and fertilisers has received special attention (Clark et al., 2018; Mutale and Xianbao, 2021).

Previous studies have found several challenges associated with adoption of precision agriculture systems. These obstacles range in type from financial to technological to environmental to political (Gerli et al., 2022). A bayesian confirmatory factor analysis of precision agricultural issued by Bosompem (2021) divided these challenges into nine primary variables: educational, economic, operator demographic, technical, data quality, high risk, time, institution-education, and incompatibility. These obstacles have greatly contributed to the slow adoption of Precision Agriculture Techniques (PATs) by farmers, especially in industrialised nations (Say et al., 2018). The major areas of concern for these identified challenges have not been fully explored by considering the uncertainties, expert elicitation and fuzzy set theories (Srinivas et al., 2020). Mintert et al. (2016) suggests that profitability, or more accurately, the inability to demonstrate that the deployment of precision agriculture technology increases farm profitability, is the primary issue preventing the widespread adoption of precision agricultural technology. Katke (2020) explains that traditionally, economic analysis of technology adoption has sought to explain adoption behaviour in terms of individual traits and resources. In the 5th chapter of this thesis, a fuzzy fault tree analysis model has been developed to identify the core challenges in relation to field-scale employment of the precision agriculture techniques in the selected study area.

2.2.2.3 Reduced tillage

The tillage practices invariably disrupt the soil surface, whereas conservation tillage techniques, including reduced tillage and no-tillage, have a notable impact on keeping soil from erosion (Lv et al., 2023). Furthermore, the implementation of conservation tillage practices has been shown to enhance soil structure. Additionally, a rise in organic matter content has been observed to elevate the infiltration-to-runoff ratio while simultaneously mitigating (Xia et al., 2020). The conservation tillage principle entails the preservation of surface soil coverage by means of retaining crop residues, which can be accomplished through the implementation of zero tillage and restricted soil disruption through mechanical means. The preservation of crop residue serves to safeguard the soil from the immediate impacts of precipitation and solar radiation, while limited soil disruption promotes soil-based biological processes and facilitates the movement of air and water within the soil. Various conservation tillage techniques are employed in modern agriculture, including but not limited to zero tillage (No-till), reduced (minimum) tillage, mulch tillage, ridge tillage, and contour tillage. The practice of no-tillage entails minimal or negligible soil surface disruption during land cultivation, with the only disturbance occurring during planting.

On the other hand, minimum tillage refers to less soil manipulation that involves ploughing using primary tillage equipment. The practice of mulch tillage involves the tillage of soil in a manner that maximizes the coverage of plant residues or other substances on the surface. The agricultural practice of ridge tillage entails the establishment of planting crops rows along either side of the ridges or on the top of the ridges. Contour tillage is the term used to describe tillage that is done perpendicular to the direction of the slope (Busari et al., 2015). Both reduced tillage and no-tillage are viable forms of conservation tillage. Clausen et al. (1996) and Xia et al. (2020) conducted their studies on identifying the impact of tillage on runoff in croplands located in Vermont, USA. Their findings indicated that reduced tillage results in a significant reduction of 64% in runoff. According to Liang et al. (2016), the implementation of no-tillage techniques resulted in a 25.9% reduction in the amount of runoff from rice-planting. Reduced and no-tillage practices mitigate the effects of tillage and rainfall by implementing soil surface protection through the use of crop residues. In contemporary times, there has been an increased utilisation of land covers and soil amendments, such as biochar, to fortify the soil structure and porosity, with the aim of safeguarding the soil as has been documented by the various studies (Awad et al., 2012; Meier et al., 2017). In their study, Won et al. (2016) employed a combination of rice straw, polyacrylamide, and gypsum to address Chinese cabbage fled. The treatment reduced suspended solids and total nitrogen by 86.6% and 34.7%, respectively. The impact of soil modification on soil loss has been investigated by Lee et al. (2015) in their research.

Several studies have indicated that any tillage system that preserves a minimum of 30% soil cover, such as reduced or no tillage, can reduce soil erosion and enhance soil structure (Seitz et al., 2018; Six et al., 2000). However, it may also lead to soil compaction in organic farming (Peigné et al., 2018). Reduced or no tillage systems offer the benefit of increased soil surface coverage throughout the year, as well as improved protection of soil structure and structure-forming soil organisms, such as earthworms (Blanco-Canqui, 2008; Mikha and Rice, 2004). The advantages of these methodologies are heightened when implemented in conjunction with varied crop rotation and sustained soil coverage to safeguard topsoil from particle detachment. The practice of reduced tillage involves minimising the frequency of mechanical operations for seedbed preparation while ensuring crop growth, rather than completely abandoning such operations (Seitz et al., 2018). The implementation of conservation tillage techniques in organic farming has garnered growing attention in recent years, as evidenced by studies conducted by Armengot et al. (2015) and Cooper et al. (2016).

However, it remains unclear whether the combination of organic farming and reduced tillage has any effect on soil erosion. Also, the comparison between conservation or no tillage in conventional conditions and tilled organic systems remains ambiguous. The significance of investigating this subject matter lies in the assessment and potential enhancement of soil erosion control in diverse agricultural frameworks, as highlighted by Hösl and Strauss (2016).

2.2.3 Process control and End treatment BMPs

The process control methods are used to reduce pollution during the conveyance of agricultural runoff to waterbodies. And the agricultural runoff end treatment practices are the final line of defence before nutrients enter the receiving water downstream. It has been proven through the implementation of BMPs all over the world that vegetative filter strips, riparian buffers, grass swales, detention ponds, ecological ditches, etc., aid in the reduction of nutrients (i.e., total phosphorous (TP), ammonical nitrogen (NH_3N)/nitrate nitrogen (NO_3), total suspended solids (TSS), chemical oxygen demand (COD), among other pollutants. However, the effectiveness of each approach varies depending on several variables. For instance, the considerations of breadth, soil type, vegetation type, etc. effects the performance of vegetative filter strips. The vegetative filter strips can remove up to 81% of TSS, 72% of COD, and 66% of TP. Additionally, grass swales contribute to a reduction in TSS of 70% to 86%, COD of 46% to 63%, TN of 14% to 20%, and TP of 34% to 77%. Another sediment control technique is silt fence, which can aid in a decrease of between 50% and 90%. Constructed wetlands are also effective in reducing heavy metals concentrations (Copper 99%, Zinc 97%, Cadmium 99%), and TSS (28%-93%) etc.

Constructed wetlands, founded on the biological treatment systems, controls sediment and nutrient runoff at the urban and watershed scales (Qiu et al., 2019). Constructed wetlands serve as zone of transition between farmland and the receiving water, with good organic matter and nitrogen and phosphorus particle absorption, adsorption, and physical settling ability. According to Díaz et al. (2012) and Xia et al. (2020), the main variables affecting pollution load concentrations in constructed wetlands are water evaporation, infiltration processes, plant features, and hydraulic retention time. Also, wetlands' removal varies seasonally. According to research by Valkama et al., TP removal efficiency peaked in June (28%) and was lowest in February (5.5%), whereas TN removal efficiency peaked in July (82%) and was lowest in November (3.5%) (Valkama et al., 2017). According to Parde et al. (2021), constructed wetlands can perform remarkably well and can achieve up to 80 to 91%, 60 to 85%, and 80 to 95% reduction in Biochemical Oxygen Demand, Chemical Oxygen Demand, and Total Suspended Solids respectively provided operation under low hydraulic loading rates. Constructed wetlands depend on soil absorption and phytoremediation much like ecological ditches do. These are regarded as a useful end treatment method because of its many benefits (such as low cost, simple operation, and simple maintenance) (Parde et al., 2021; Wu et al., 2015).

Due to its simple construction and minimal maintenance requirements, vegetative filter strips have been often used for mitigating agricultural nonpoint source pollution in several countries (Jain and Singh, 2019; Krutz et al., 2005). According to an experimental investigation conducted in Virginia, these strips can remove around 70% of suspended particles, 61% of phosphorus, and 54% of nitrogen (Dillaha et al., 1989). However, it was discovered that the silt build-up causes the vegetative filter strips' efficiency to decline with time. A research conducted in Canada, showed that the average phosphorous trapping capacity of vegetative filter strips is around 61%, ranging from 31% when using a 2 m filter to 89% when using a 15 m filter (Abu-Zreig et al., 2003). In order to maximise the increase in water quality, the design of the vegetative filter strips should be such that the area of the buffer strip interacting with the flow is kept to a minimum. Therefore, while employing vegetative filter strips for NPS pollution management, it is crucial to consider the size of the strip, the pace at which sediment is removed, and topographic variables. These strips, however, requires a sizable amount of land, that might not become possible for the tiny landholdings. Yu et al. (2019) have conducted a comprehensive review on the transport characteristics and different models of vegetative filter strips for different types of contaminants.

The ecological ditch is an artificial structure designed to eliminate nutrients from agricultural runoff through various processes such as sorption, sedimentation, transformation, plant uptake, and microbial metabolic activities, as documented in sources (Dollinger et al., 2015; Xia et al., 2020). Agricultural ditches are extensively distributed throughout farmland and are recognised as a crucial component of both drainage and irrigation systems. The presence of periphyton is a crucial element in the composition of ecological ditches. The substance has a broad distribution in natural aquatic systems and has the potential to facilitate the elimination of water contaminants through absorption, adsorption, and complexation mechanisms. Periphyton possesses a substantial biomass and exhibits a high degree of sensitivity to water quality rendering it efficacious in the removal of nitrogen and phosphorus, among other benefits. Pierobon et al. (2013) have carried out experiments on N removal in ecological ditches located in the Po River Basin of Italy. The ditches were both vegetated (with Phragmites australis and Typha) and unvegetated. The findings indicate that the vegetated ditches exhibited an average removal capacity of 1.52 kg N km^{-1} day^{-1}, which was notably higher than the removal capacity of 0.24 kg N km^{-1} day^{-1} observed in the unvegetated ditches. The aforementioned observation suggests that the presence of aquatic vegetation is of utmost importance in the interdependent relationship between sediment, aquatic plants, and microorganisms. Further the research highlights that the removal capacity of ecological ditches is significantly impacted by the diversity of plants. Hence, the meticulous choice of exceptionally effective aquatic plants assumes significance in the domain of ecological ditch investigation. Plants have the ability to amass substantial quantities of nutrients for their own growth during the periods of active growth. Although, the capacity for accumulation diminishes progressively with the onset of senescence (Menon and Holland, 2014).

In addition, the process of plant decomposition is known to result in the emancipation of previously sequestered nutrients, thereby serving as an additional nutrient reservoir (Kröger et al., 2007). The management of harvest is therefore a crucial component of ecological ditch management, nevertheless necessitating further comprehensive investigations (Kumwimba et al., 2021). The comprehensive elimination of nutrients within ecological ditches is achieved through plant harvesting. Thus, on-time collection of aquatic vegetation from ecological ditches can efficiently enhance nutrient elimination and facilitate plant rejuvenation. However, the management of ecological ditches has perennially posed a challenging issue. The process of large-scale harvesting necessitates a significant amount of labour, thereby leading to a substantial rise in maintenance expenses. According to research, smallholders and family farming are the primary modes of agriculture in Asia and Latin America. The expenses associated with such operations are often expensive for individuals engaged in small-scale agriculture. As a result, the implementation of ecological ditches in such areas is hindered.

Riparian buffer zones are present in agricultural settings as transitional areas that separate agricultural land from either natural waterway, such as streams, or man-made waterways, such as farm drains. The habitats that can be encompassed by this category are diverse and may comprise physical features such as grass strips, forested regions, and wetlands. The significance of riparian zones in the agricultural landscape lies in their ability to mitigate the presence of Nitrate and other contaminants, such as phosphorus, in runoff (Luo et al., 2017).

The effectiveness of riparian buffer zones could be delineated by three distinct features: removal efficiency, retention capacity or mass removal, and specific removal. These characteristics are expressed as a percentage, mass removed per hectare per year, and percentage per metre, respectively (Mander, 2008). Riparian buffer zones serve several crucial functions including the filtration of polluted overland and subsurface flow from intensively managed adjacent agricultural fields, protection of water body banks against erosion, filtration of polluted air, particularly from local sources such as big farm complexes and fields treated with agrochemicals.

Yet some other functions of riparian buffers entail, prevention of the intensive growth of aquatic macrophytes through shading by canopies, improvement of the microclimate in adjacent fields, creation of new habitats in land/inland water ecotones, and enhancement of connectivity in landscapes through migration corridors and steppingstones (Mander, 2008). The riparian buffers present a promising opportunity to mitigate the effects of climate change (Cole et al., 2020). This is achieved through the reduction of organic matter, nutrients, as well as the harvesting of nutrients, such as nitrate, via denitrification (Delgado et al., 2013). The potential of certain conservation practices to function as nutrient sinks, thereby impeding the transfer of nutrients from upland agricultural fields to streams, has been documented in various studies (Hill, 1996; Mayer et al., 2007; Vidon, 2010). Buffers and vegetative filters have the potential to yield economic benefits through their utilisation as biomass and forage sources under regulated circumstances. It is imperative to consider the net greenhouse gas balance resulting from these practices, particularly in wetlands and riparian buffer zones where anaerobic conditions may lead to the emission of CH_4 and N_2O. This has been highlighted in previous studies by Conrad (2007) and Kim et al. (2009a, 2009b). Further investigation is required to determine the impact of utilising riparian buffers, and wetland systems on the overall carbon balance and the release of trace gases, including N_2O and CH_4. Additionally, more research is necessary to understand the potential effects of climate change on these balances and fluxes. Thus, such methods may help to conserve the environment along with achieving reasonable profits (Cole et al., 2020). These methods aim for sustainable practices which have least interference with the natural processes in comparison to other artificially designed techniques. In order to better understand the nutrient reduction potential of BMPs, watershed models need to be developed.

2.3 Watershed models for agricultural non-point source pollution assessment

The comprehension and the management of water resource challenges observes intricate mechanisms and interplays occurring at the surface, subsurface, and their intersections. Water quality policies are increasingly demanding comprehensive approaches to analyse and maintain water resources, to address these wide range of interactions. Various models at the watershed scale have been created to aid in the prediction of non-point source pollution. The utilisation of a watershed model allows for a comprehensive simulation of hydrologic processes, in contrast to other models that concentrate on singular or numerous operations at a smaller scale, without the complete integration of the watershed region. The utilisation of watershed-scale modelling has become a significant scientific and managerial instrument, especially in endeavours aimed at comprehending and regulating water contamination (Apostel et al., 2021; Daniel, 2011; Rallapalli et al., 2022; Srinivas et al., 2020). Towards implementation of suitable BMPs for addressing the water quality problems for a given watershed system, there are numerous watershed modeling tools which can study the nexus of land-water-air-plant-human, with each watershed model having its own capabilities and limitations in assessing different hydrological processes. These models take inputs from different physical and environmental characteristics of a catchment in the given watershed like soil, flow, land cover characteristics, precipitation, temperature, topology, etc. (Gull and Shah, 2020). The results obtained from these models help to assess water quality, developing water resource management strategies, accounting for NPS pollution influx to the waterbody at watershed scale. These tools provide specific help in understanding and limiting the water pollution. There are number of watershed models can be selected as per the study objective.

These models could be categorized based on their spatial characteristics i.e., lumped, semi-distributed, and distributed models. The lumped modelling approach is a method of computation that treats a watershed as a singular unit, whereby the parameters and variables of the watershed are averaged across the watershed. Semi-distributed and distributed models are superior to lumped models as they work out the hydrologic processes, inputs, physical boundary constraints, and watershed variables considering the spatial variability. In the context of semi-distributed models, it is common practice to permit partial spatial variation of the quantities. This is achieved by partitioning the basin into multiple sub-basins, which are subsequently treated as a single unit. The representation of spatial heterogeneity in distributed models is commonly determined by the modeler, with a resolution that is typically specified (Daniel, 2011; Liu and Weller, 2008).

Further, these models could be apportioned into two distinct categories, namely empirical or statistical and physical or process based. Empirical models are employed to establish empirical correlations between hydrological parameters, which include methods like hydrograph separation, export coefficient, etc. These techniques commonly referred to as black box often fail to incorporate the pollution process and its underlying mechanisms (Alarie et al., 2021; Sayed et al., 2023). One of the benefits associated with these models is their reduced input data requirement and lesser complex calculation methodology. Nevertheless, the models exhibit limitations in accurately depicting the process of contaminant migration and are unsuitable for application in expansive or wide-ranging regions due to their inherent localised features. The integration of hydrological models, soil erosion models, and contaminants transport models constitutes a physically based modelling approach, which yields a comprehensive system. These models provide a quantitative description of the continuous process of NPS pollution occurrence. The research methods referred to as "white-box" models are characterised by their focus on the internal mechanisms of the pollution process (Sayed et al., 2023; Shen et al., 2012). These models employ physically based equations to depict these processes (Wang et al., 2008). The technology industry offers a range of physically based models that have gained widespread acceptance, such as, AGricultural Non-Point Source Pollution Model (AGNPS), Hydrological Simulation Program - FORTRAN (HSPF), MIKE SHE, and Soil and Water Assessment Tool (SWAT). Some the relevant and wide-used watershed models, including their research applications are briefly discussed below:

(a) SWAT model: It is a semi-distributed watershed model which could function on different time scales (from sub-daily to annual) and take into account the topography of the watershed, weather patterns, hydrological processes, and agricultural practices (Apostel et al., 2021; Zhou et al., 2016). The watershed is split down into subbasins, which are then separated into hydrological response units (HRUs), which reflect unique combinations of soil and land-use characteristics. The four storage volumes: snow, topsoil (0–2 m), shallow aquifer (2–20 m), and deep aquifer (>20 m), are exercised to assess the water balance corresponding to respective HRU's in the watershed. SWAT is preferred over other watershed models because it can run continuous long-term simulations in primarily agricultural watersheds and reproduce the impact of episodic rainfall events at finer (i.e., daily or sub-daily) resolutions. With a large user base and an active technical support forum, SWAT may be used anywhere in the globe. A vibrant community of model developers has consistently contributed to enhancing process representations and enhancing the model's capabilities. In order to better simulate agricultural activities in arid and semi-arid environments, modular programs, tools, and algorithms have been developed (Ouessar et al., 2009; Samimi et al., 2020). Examples of specific technological advancements that enhance SWAT performance in arid and semi-arid irrigated agricultural settings include the ability to simulate crop rotation (Marek et al., 2017) and the use of the modified plant growth module of winter wheat to estimate crop yields (Sun and Ren, 2013). Additionally, coupling SWAT with other models has made it possible to utilise the advantages of various models (Priya and Manjula, 2021; Sarkar et al., 2019).

(b) HSPF: The HSPF model is an effective watershed model that is semi-distributed and temporally continuous and was created with the assistance of the Environmental Protection Agency to simulate water quality processes in both natural and artificial systems. The HSPF model is uniquely equipped to conduct comprehensive simulations of soil and contaminant runoff mechanisms while also accounting for sediment-chemical and hydraulic processes within the stream. The HSPF model is widely regarded as a highly adaptable and all-encompassing tool for assessing water quality on a watershed basis (Roostaee and Deng, 2022). Simulating and calibrating water quality using the HSPF model is notably more challenging than hydrologic simulation, as it involves intricate chemical interactions, transport processes within streams, and a significant number of parameters. This has been highlighted in a study by Luo et al. (2017). The parameters of the HSPF model can be classified into two distinct groups, namely fixed parameters and process-related parameters, as stated by Al-Abed and Whiteley (2002). The values of fixed parameters, such as type of soil, are held constant throughout the calibration process and do not need to be incorporated into the sensitivity analysis. Additionally, the calibration of the HSPF model is a hierarchical procedure that commences with hydrologic calibration and subsequently proceeds to the sediment calibration. The HSPF model has been widely utilised in various applications such as flow simulation, dissolved oxygen and nutrient modelling, sediment transport and fate processes, best management practices, transportation of pesticide and herbicide, bacteria modelling, and heavy metal transport, such as mercury (Albek et al., 2004; Lee et al., 2021; Mishra et al., 2007; Patil et al., 2013, 2011; Patil and Deng, 2012; Rolle et al., 2012; Stella 2020).

(c) AGNPS: This model was created with the purpose of examining and producing approximations of the quality of runoff water in agricultural watersheds (Mulla et al., 2019). The advancement of a persistent rendition of a single incident in the model are underway since a couple of decades. The Annualized AGNPS (AnnAGNPS), which is a continuous version of an Agricultural Non-Point Source model that is annualised. AnnAGNPS v5.5 is the most recent upgraded version. This watershed evaluation tool is extensively utilised and was collaboratively created by the U.S. Department of Agriculture - Agricultural Research Service (USDA-ARS) and the Natural Resources Conservation Service (NRCS). The model in question is a distributed parameter model that operates continuously and is employed to approximate the transport of pollutants, soil erosion, and surface runoff in watersheds of varying sizes, ranging from a few hectares to tens of thousands of hectares, while accounting for different environmental conditions (Zhang et al., 2020). This model is a pollutant loading model that utilises a batch process and continuous-simulation approach to simulate surface-runoff. The watershed is divided into cells that represent various erosion types, including ephemeral gully and sheet and rill erosion and the effects of conservation practices. The attributes and inputs of a watershed are represented at the individual cell level. The physical and chemical components originating from the land area undergo routing processes, which result in their deposition throughout the river channel system or their transportation off the watershed. The AnnAGNPS model has the capability to simulate hydrological features, erosion, nitrogen (N) and phosphorus (P) migration in a complex landscape, as compared to other models that assess agricultural BMPs. Additionally, the model has been found to have high precision and good versatility in modelling the NPS pollution of agriculturally dominated watersheds.

Soil and water assessment tool (SWAT) and Hydrologic simulation program-Fortran (HSPF) are two models, which are competent in assessing the NPS pollution in farms and water lands. Similarly, there are models like Agricultural non-point source (AGNPS), Storm water management model (SWMM) etc. Each model has its constraints and advantages, and suitability for area i.e., urban area or agricultural area etc. (Wang et al., 2020). These models are useful in understanding the intricate processes involved in NPS pollution generation and also to assess their impact on the water quality, suggesting BMPs to achieve water quality standards (Liu et al., 2015; Mittelstet et al., 2016; Strauch et al., 2013). Fu et al. (2019) explored the Scopus database and found 3282 research articles concerning water quality models in the environmental field within the timeframe of 2003 to 2018. Amongst the 42 surveyed water quality models, the authors selected five main catchment-scale models, namely: SWAT, HSPF, Integrated Catchment Model, eWater Source, and SPAtially Referenced Regressions On Watershed attributes (SPARROW) and critiqued their ability through 10 attributes characterized by model use, model development, and model performance categories. Li et al. (2015) used SWAT for quantifying both the individual and the combined effect of land cover change and climate on runoff in Han and Luan River in China. Mittelstet et al. (2016) assessed the cost-effectiveness of BMP in controlling agricultural NPS for Three Gorges Reservoir, China. Xie and Lian (2013) conducted a comparative analysis study on parametric uncertainties calibration between SWAT and HSPF models concluding that when the calibration parameters are optimized both models performed good in simulating the Illinois River. Annualized Agricultural Non-Point Source Pollution Model (AnnAGNPS) has been extensively used for estimating NPS pollution and water quality. For instance, Karki et. al. (2017) used AnnAGNPS for an agricultural watershed in East-central Mississippi to estimate sediment, nutrient, and runoff. Srinivas et al. (2020) compared Agricultural Conservation Planning Framework (ACPF), Prioritize, Target, and Measure Application (PTMApp) and HSPF- Scenario Application Manager (SAM) to assess their feasibility towards field scale modeling of rainfall-runoff processes to suggest BMPs in a targeted manner.

The task of providing dependable water resources to an expanding populace and competently assessing the pollution of surface and groundwater are becoming progressively intricate and interconnected predicaments for water resource administrators, engineers, and scholars. The challenges require the implementation of a comprehensive methodology/models that can analyse distinct procedures and structures, as well as their interconnection. This synthesis reviewed and employed current technologies and issues involved. The utilization of these techniques offers advantages in supporting water resource and watershed managers in diverse applications, including the assessment and formulation of Total Maximum Daily Loads (TMDLs). In order to ease the watershed decision making process using model outcomes, soft computing and geoinformatics tools play a significant role.

2.4 Soft computing and geoinformatics

The watershed models discussed in the previous section utilise a physically based methodology to simulate intricate watershed phenomena across various spatial and temporal dimensions. Typically, it is required to describe the inputs of the watershed system, the physical laws that govern its behaviour, and the boundary and initial conditions while developing these models (Daniel, 2011; Koo et al., 2020; Preis and Ostfeld, 2008). The utilisation of GIS and remote sensing has been acknowledged as valuable techniques in the processing of unprocessed data to generate model input and in the synthesis of spatial data during the modelling procedure (Kang and Park, 2003; Quinn et al., 2019), thereby serving as effective tools. The utilisation of a GIS as a pre-processor and postprocessor to watershed models is a widely observed phenomenon. This is evident in the incorporation of GIS in two distinct models: SWAT and Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS). As per Kang et al. (2006), a pre-processor is usually integrated into a model framework to furnish formatted input data single/multiple layers. On the other hand, postprocessors serve the purpose of facilitating the visualisation of model output and displaying simulation results in a graphical format. The Geographic Information System (GIS) is particularly advantageous when dealing with a map-based visualisation. The utilisation of GIS technology facilitates the spatial modelling of data, wherein maps containing essential information on the quality of water and other significant geomorphological factors are generated. This approach enables decision makers to gain a holistic perspective of the target area, which is crucial in the development of Total Maximum Daily Load (TMDL). The utilisation of spatial modelling techniques can aid in the selection and arrangement of data in a necessary format for input into water quality models, specifically those utilised in the development of TMDL assessments for both watershed and receiving water systems. Numerous instances of this pre-processing methodology can be found in scholarly works, wherein GIS is utilised for the initial pre-processing stage (Quinn et al., 2019; Ramirez et al., 2005; Viers et al., 2012). In addition, GIS plays a crucial role in the post-analysis of modelled outcomes and devising remedial or mitigative measures. This includes identifying optimal structural best management practices and directing non-structural best management practices towards areas with high impact.

Remote sensing primarily utilising satellites is progressively becoming more prevalent as an ancillary means of obtaining data. Today, in several instances, it is the sole viable source of information. Recent advancements in satellite-based sensors have enabled the acquisition of both direct and indirect measurements pertaining to almost all aspects of the hydrological cycle (Lettenmaier et al., 2015; Shah et al., 2021; Sheffield et al., 2018). The aforementioned factors comprise precipitation, evaporation, levels of lakes and rivers, surface water, soil water content, the snow and the aggregate water storage encompassing both surface and subsurface water. According to van Dijk and Renzullo (2011), the sensors possess the ability to furnish vital data for water management and hazard tracking, including the assessment of their consequences. The utilisation of remote sensing retrievals to assess the fluctuation in vegetation state, plant productivity, and health has a lengthy history. This approach has practical applications in agricultural monitoring, assessment, and planning. Satellite data's extensive coverage, including global coverage, facilitates the evaluation of risk concerning regional water security, agricultural production, storage, and trade (Dalin et al., 2017; Jones et al., 2009; Jung et al., 2021). Despite being in their early stages, certain satellite remote sensing products possess considerable limitations, challenges, and caveats in their application for water resource management. Nevertheless, their extensive spatial coverage and superior temporal resolution (sub daily for geostationary and equatorial orbiting satellites) enable them to furnish nearly global information in near real time.

The models like Watershed Analysis Risk Management Framework (WARMF) and HSPF exclusively incorporate use of GIS platform (TMDL, 2017). Ramirez et.al. (2005) used 5-meter spatial resolution hyperspectral imagery and GIS to obtain potential mass wasting sites. They also mention that use of hyperspectral imagery is a promising approach for TMDL assessment for coming time. Kang et al. (2006) simulated water quality for a watershed containing paddy fields to engender TMDL using GIS and remote sensing. Tairi et. al. (2021) mapped or quantified soil erosion for Tifnout Askaoun watershed by applying Revised Universal Soil Loss Equation (RUSLE) in GIS platform.

The conventional methods utilised for the creation of inputs and boundary conditions for watershed models are known to be computationally demanding, necessitating substantial amounts of data and calibration. To tackle the aforementioned concerns, scholars (Daniel, 2011; Dodangeh et al., 2021; Naseri et al., 2021; Reshmidevi et al., 2009; Wu et al., 1999) have adopted a data-centric methodology that leverages soft computing techniques such as fuzzy logic, genetic algorithms, and other optimisation algorithms. The random nature of natural events or the random nature of the meteorological data like precipitation, temperature, and flow of stream, give rise to uncertainties. There are additional uncertainties coming from missing data, pollution control regulations, and complex hydrodynamic computations in the watershed models like SWAT and HSPF (Rehana and Mujumdar, 2009; Srinivas and Singh, 2018; Xie and Lian; 2013; Zhang et al., 2014). Such deficiencies are important to address in order to avoid the biasedness resulting in development of decision support framework for controlling NPS pollution. Fuzzy logic concepts are adept in addressing the aforementioned vagueness and uncertainties (Srinivas and Singh, 2018).

The modelling approach utilised in fuzzy logic is grounded on the theoretical framework of fuzzy sets. This approach involves the verbal definition of relationships, as opposed to the utilisation of established physical relationships. In the realm of set theory, the conventional approach involves designating an object as either belonging to a set (1) or not belonging to a set (0). However, the concept of a fuzzy set permits the existence of intermediate degrees of membership that lie between complete membership and complete non-membership. The primary objective is to establish functions or membership functions which are fuzzy in nature and delineate the associations between the input variables and the system's outputs (Mahabir et al., 2003). The two primary fuzzy logic-based modelling systems are: Fuzzy inference systems operate on pre-existing rule-bases primarily informed by expert knowledge. Secondly, fuzzy adaptive systems, these can automatically construct and modify its rule-base using sample or training data.

The chapter 3,5, and 7 of this thesis expounds and employ various shades of the fuzzy-based approaches for developing BMP adoption decision support frameworks. Fuzzy logic-based models possess two notable benefits, namely their capacity to tolerate errors and their ability to incorporate the expertise of water resource experts (Casper et al., 2007). The fuzzy logic methodology is highly appropriate for analysing watersheds, given that numerous environmental factors are optimally represented as gradients. Yu and Yang (2000) suggest that fuzzy logic has potential applications in hydrologic modelling. In this context, a hydrologist may utilise linguistic expressions, such as "bad" and "good," to define the acceptable degree of simulation based on their expert judgement and knowledge. Fuzzy logic has been effectively utilised by researchers in addressing water resource challenges and hydrologic process modelling (Kambalimath and Deka, 2020). These applications include infiltration, contaminant fate and transport, precipitation event reconstruction, rainfall-runoff modelling, etc. These achievements have been documented in various studies (Bárdossy and

Disse, 1993; Dodangeh et al., 2021; Hession and Shanholtz, 1988; Hundecha et al., 2001; Kambalimath and Deka, 2020; Özelkan and Duckstein, 2001). Liu et. al. (2020) applied fuzzy approach to handle parametric uncertainties in SWAT model. There are many multi criteria decision making problems which have been solved using Fuzzy analytical hierarchy process (FAHP) (Azarnivand et al., 2015; Celik et al., 2009). For example, Hembram and Saha (2020) performed erodibility prioritization for Jainti River sub-watersheds using FAHP.

Other soft computing techniques such as genetic algorithms because of their ability to replicate the system behaviour without having explicit understanding of the physical system involved, are also efficient tools for data forecasting and prediction. Thus, the run-off prediction, climatic processes and land uses patterns can be well forecasted using these models (Maringanti et al., 2009; Noori and Kalin, 2016; Pradhan et al., 2020). Also, there is a substantial use of optimization algorithms for optimal design of BMPs for given watershed systems. Many algorithms such as ant colony optimization, genetic algorithms, particle swam optimization etc. have been extensively used for optimizing BMP allocation in a watershed system. Among these, genetic algorithms are most used to decipher optimal design (Khan et al., 2022; Maringanti et al., 2009; Naseri et al., 2021). Genetic Algorithms are a type of nonlinear optimisation search methodology that emulates the biological processes/theories of natural selection as well as the survival of the fittest (Daniel, 2011; Holland, 1992). One notable distinction between genetic algorithms and other conventional optimisation techniques is that genetic algorithms operates on a set of potential solutions, whereas classical optimisation techniques operate on a single solution (Ritzel et al., 1994). Several initial research endeavours have exhibited the efficacy of genetic algorithms in the context of water resources applications. Ritzel et al. (1994) utilised a genetic algorithm approach in addressing issues related to groundwater contamination. Several other scholars (Daniel, 2011; Liong et al., 2007) have made notable contributions in enhancing and refining rainfall-runoff models through the utilisation of genetic algorithm. These technologies are now also emerging in agricultural field, these are particularly advantageous and helpful in precision agriculture (Talaviya et al., 2020).

CHAPTER 3

Research gaps, Objectives, and Scope

The discussion in earlier chapter implies that there has been extensive research done in developing various models/strategies to tackle non-point source pollution in the waterbodies by combining various approaches encompassing the use of BMPs, watershed models, etc. The research in this direction is current, and researchers are coming up with novel models having different combinations for search algorithms, modelling techniques, etc. to identify a robust optimization technique for adopting BMPs in a watershed system worldwide (Ji et al., 2022; Li et al., 2023; Liu et al., 2019). In the Indian context, the research to identify a suitable BMP in a comprehensive manner (i.e., considering the set of both structural and non-structural BMPs) at a field-scale is very limited. Most of the research is restricted to the selection of an agricultural BMPs only (Uniyal et al., 2020). Further, the research on selection of BMPs satisfying economical and socioeconomically considerations using multi-objective optimization tools is still meagre (Himanshu et al., 2019).

3.1 Identified research gaps

This research work is intended to fulfil the research gaps concerning effective implementation of BMPs at the field-scale considering multiple objectives such as environmental, ecological, hydrological aspects. With the use of soft computing techniques, remote sensing, and sensor technology, the effectiveness of BMP allocation can be significantly enhanced. The goal of this research is to engender simple, robust, and scientific decision support framework for watershed modeling for the selected regions in USA and India using RS technology and GIS which also incorporates considerations from environmental, economic, hydrologic, socio-economic, agronomic factors. Following are some of the major identified research gaps:

1) Contemporary research lacks consideration of economical, agronomical and socioeconomical aspects in conjunction with hydrological and ecological aspects while suggesting BMPs for a watershed system.
2) To the best of knowledge, existing models for BMP implementation in Indian watersheds do not use optimization techniques for optimizing economic and water quality benefits.

3) The conventional models like SWAT, HSPF etc. suggests conservation practices at sub-basin levels which is inefficient for targeted field-scale (or practical on-ground) implementation of conservation practices.
4) The field-scale application of BMPs requires consent of multiple stakeholders like landowners, farmers, and watershed planners etc. which current models do not consider.
5) Absence of US watershed's BMPs study from the viewpoint of their implementation in India.
6) No frameworks to identify the challenges associated with precision agriculture in India, especially in the study area.
7) Lack of crop rotation practices in the study area in India to enhance soil fertility, profits and reduce water requirements.

3.2 Objectives of the proposed research

The primary objective of the study is to develop decision support frameworks by the dint of suggesting effective conservation solutions for inculcating sustainability in the modern agriculture system and thereby restoring the pristinity of the waterbodies by limiting non-point source pollution runoff. The main objectives of the proposed research are:

1.) Developing farmer-driven decision support frameworks to leverage source, process, and end control BMPs application considering agronomic, socioeconomic, hydrological, and economic factors.
2.) Handling data uncertainty using soft computing enabled GIS models and tools for effective prediction of diversified agriculture patterns.
3.) Developing GIS/Soft computing-based models for handling non-point sources of pollution.
4.) Modelling non-point sources of pollution followed by Total maximum daily loads (TMDL) scenario assessment.
5.) Development of a user-friendly i.e., simple, and robust decision support system by employing optimization techniques to suggest a set of optimal practices to achieve the non-point pollution reduction, cost efficiency etc. while ensuring their field level adoption.

The present study attempts to evaluate and suggest sustainable approaches for controlling ANPS pollution and their transfer to the Ganga/Yamuna and Mississippi Rivers for the selected agriculture dominating watersheds in the India and USA (Fig. 1.1 and 1.2) while simultaneously learning lessons from USA's NPS pollution management. The suggested sustainable decision support frameworks not only develop sound watershed planning scenarios, but also confirms the amalgamated, scientifically-sound water quality data. The present study has developed flexible modelling frameworks that integrates fuzzy logic, geoinformatics, watershed modeling, and optimization techniques. This framework is characterised by its flexibility and its ability to handle the uncertainty and imprecision that are commonly associated with the criteria and decision makers involved in river basin planning. The utilisation of Geographic Information Systems (GIS) augments the process of decision making through the presentation of outcomes in a spatial context. In general, this research study provides fundamental tools to policymakers for formulating management strategies aimed at promoting sustainability in the river ecosystems.

3.3 Scope of the research

Excessive exploitation of soil and climate variations have worsened the water erosion and transport of nutrients to the surface waterbodies, thus, adversely impacting the global economy and environment. Therefore, the present research develops prompt, effective, and systematic frameworks for addressing the worldwide daunting issues of river water impairment by non-point source pollution discharge from the agricultural fields. The study also learns lessons from the USA's ANPS management experiences particularly in relation to the advanced modelling techniques and implementation of innovative BMPs. And develops decision support frameworks that are useful guides for the policy makers and aid in developing sustainable as well as economically sound management scenarios for protecting land and surface waterbodies degradation. The proposed methods use both qualitative and quantitative approaches and incorporate methods and learnings of environmental science, economics, agronomy, and hydrology. The agriculturally dominated land bounded by the two iconic rivers flowing in India – Ganga and Yamuna and the selected watersheds in the Mississippi River basin in USA have been chosen as the study area for citing sustainable conservation practices and examining the developed frameworks. The study developed novel decision support tools incorporating stochastic, fuzzy-based, remote sensing, ArcGIS

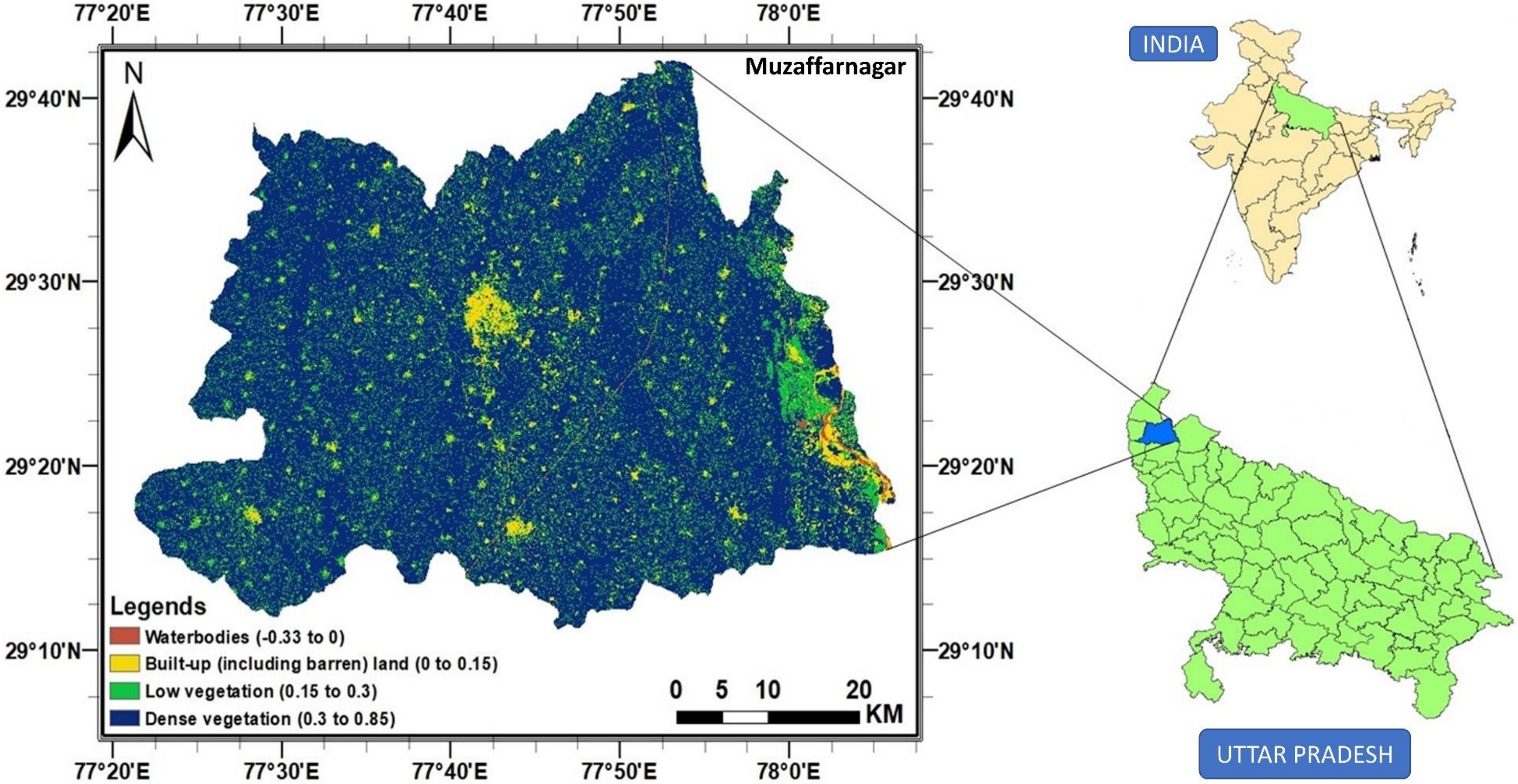


Fig. 3.1 NDVI map for the Muzaffarnagar study region in Uttar Pradesh, India.

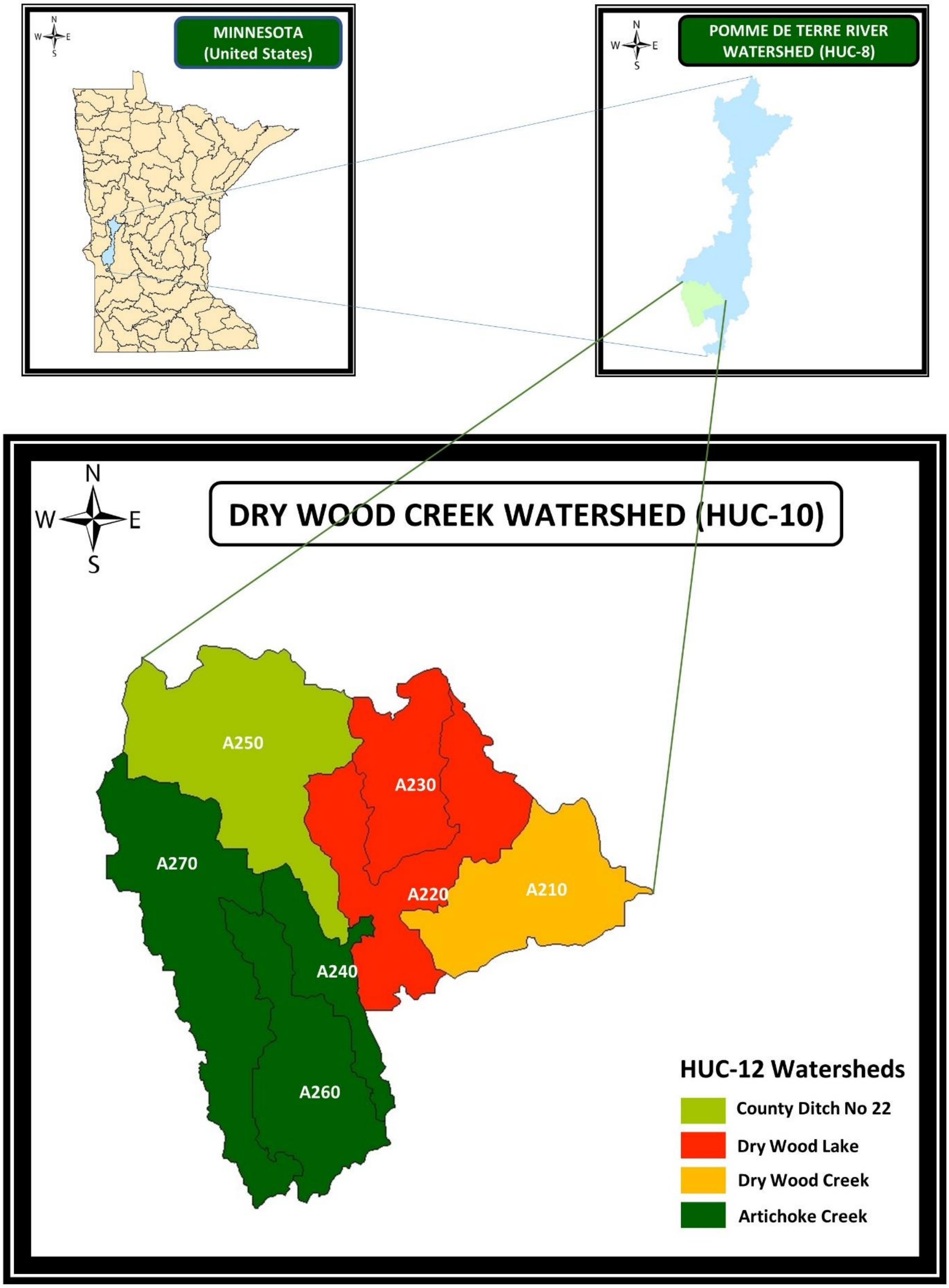


Fig. 3.2 Dry Wood Creek watershed and its sub-watersheds' location in the United States

platform, interviews, and guidance from watershed planning and agronomy experts, local stakeholders, and farmers. Further, the required data was acquired from organizations like the Indian Council of Agricultural Research (ICAR), Central Pollution Control Board (CPCB), Department of Irrigation, Central Water Commission (CWC), Minnesota Pollution Control Agency (MPCA), United States Environmental Protection Agency (USEPA), and other web-based geospatial datasets. The study utilized the original and as recent possible datasets for the study areas varying in duration (pertaining to their inherent nature) ranging from an instance to 12 years. The models developed are universally applicable, provided the necessary alterations subjective to the study location have been made; the details corresponding to these are provided in the following sections.

CHAPTER 4

GEOINFORMATICS AND STOCHASTIC OPTIMIZATION FOR SUSTAINABLE AGRARIAN MANAGEMENT

4.1 Introduction

Land degradation is one of the most serious environmental threats worldwide (Chasek et al., 2019; Prăvălie et al., 2021) as it causes food insecurity, loss of flora & fauna, climate change and ecosystem imbalance. Scientific surveys reveal that the unsustainable agricultural practices is the prime cause of degradation of soil fertility, which may cause degradation of 95% of the Earth’s land by 2050 (GEF, 2021). For instance, the general tendency of the farmers is to practice excessive cropping of profitable crops leading to land degradation. Like, sugarcane is the principal cash crop of the studied region followed by wheat and paddy. Sugarcane crop is known for its intensive water requirements. Concurrently, farmers use flood irrigation for crop cultivation, which requires a significant amount of water. This has caused abrupt hydraulic gradients in groundwater level (Tyagi et al., 2009; Umar et al., 2006).

The Indo-Gangetic plains (study area) is an agriculture intensive region which contributes to about 50% of the total nation’s production (Pal et al., 2009). Uttar Pradesh is one major state lying in this region and is encountering critical agro-ecological challenges such as decreasing agricultural productivity, rising soil salinity and lowering of ground water tables (Panigrahy et al., 2010). The United States’ response to agricultural land use management includes pollution restrictions like the United States Environmental Protection Agency’s Total Maximum Daily Loads (USEPA, 2010) and adoption of Best Management Practices (BMP) (Jiang et al., 2020). The European Union is also examining the prospects of the Functional Land Management (FLM) concept, which is basically a framework for appropriate land use selection based on respective soils’ potentials (Jiang et al., 2021; Schulte et al., 2015, 2014; Vrebos et al., 2017). All soils provide all ecosystem services such as food and fuel production, water quality improvement, carbon sequestration, biodiversity habitat, and nutrient recycling. However, the different soils perform different ecosystem services with varying effectiveness. The FLM approach best aligns landscapes capabilities to attain the most efficient and effective economic and ecosystem services for the targeted watershed.

The Best management practices (BMPs) are unanimously recognized (Jain and Singh, 2019; Opoku-Kwanowaa et al., 2020; Prokopy et al., 2008; Wang et al., 2019) as the ways for sustaining agricultural land's productivity and improving surface and groundwater quality. The management of soil fertility is pivotal to the endowment of quality food and water supply (Fiorentino et al., 2018). In context of improving soil fertility, the set of BMPs include crop rotation, planting cover crops, irrigation management, optimum pesticide & fertilizer application, conservation tillage, etc. (Adom, 2019).

Crop rotation is a practice of cultivating dissimilar or contrasting crops in different seasons on the same land. The rotation of crops could be both cyclic and acyclic i.e., repeating the same crop sequence year after year or varying the crop sequence indefinitely. Such practices are primarily beneficial as the succeeding crop utilizes the nutrient residues released by the preceding crop thus curtails the demand of synthetic fertilizers (Askegaard and Eriksen, 2008). An efficiently designed crop rotation system can also provide organic matter to soil, which further helps in sustaining fertility of the soil and preserving healthy soil organisms' culture. Adequate soil organic matter quantity also prevents soil erosion, nutrient losses, and increases soil water holding capacity.

Further, the presence of different crop species in crop rotation cycle repels or interrupts the growth of host-specific pests or weeds (Angus et al., 2011). Thus, crop rotation practices foster soil health, controlling pests, weeds, other diseases, decrease in dependency on chemical fertilizers, increasing crop yields (Bowles et al., 2020; Tariq et al., 2019) Crop rotation practices are becoming economically productive, and their application is also observing dramatic increase in outputs from the fields of US (Afroz et al., 2021; Sindelar et al., 2016). The rotation of cover and cash crops can help benefit both the farmer's income and soil health (Huang et al., 2021). However, for a particular agricultural watershed, the number of possible suitable patterns would be mathematically enormous. For example, for 7 crops, the possible number of combinations of choosing any two crops (considering the order of crops) can be mathematically expressed as ${}^{7}P_{2}$ or $\frac{7!}{(7-2)!}$, i.e., 42. Obviously, some combination of patterns can straight forwardly be discarded based on previous agronomical experiences, still the possible options remain significant (Mohler et al., 2009). Many mathematical or computational models have been proposed for crop rotation planning problems (Santos et al., 2015; Capitanescu et al., 2017). Various cropping plans practiced by the researchers have already been discussed in the section 2.2.2.1 of literature review of this work. Although these models apply different agronomic, production, economic, and market constraints, and rules, they lack consideration of individual land potentials, subjective allocation of cropping patterns to the fields, and a framework for direct field implementation of cropping plan suggestions.

For promoting crop rotation, the criteria for selecting suitable land for a specific crop belong to different subdomains concerning climate bio-physicochemical characteristics of the land. In earlier studies, the analytical hierarchy process (AHP) and fuzzy-AHP have been extensively used for pairwise comparisons of criteria (Cobuloglu and Büyüktahtakın, 2015; Srinivas and Singh, 2018; Dedeo˘glu and Dengiz, 2019; Srinivas et al., 2020). However, these approaches have certain limitations, such as rank-reversal and allowance of only some selected predefined ranges while converting linguistic variables to fuzzy sets and also an inability to offer flexibility to the Decision Maker (DM) to choose their own scale for rating the criteria. In this chapter, we have used a stochastic pairwise comparison approach, which utilizes beta distribution for the pairwise comparison of different criteria. Unlike the limitation of fixed ranges in conventional approaches, the DM in this approach has the flexibility to define their range limits (Cobuloglu and Büyüktahtakın, 2015).

The study proposes an integrated approach linking geoinformatics, stochastic pairwise comparison (SPC), and constraint optimization for sustainable crop rotation planning to address the intimidating issues of declining water quality and quantity, soil fertility, and enhancing farmers income return based on crop rotation practices. The approach overcomes the major drawback in past crop planning models by combining the US and European Union response towards agricultural land use management, i.e., extending the FLM concept in terms of delineating the suitable crop-rotation pattern (a BMP type) for the given land based on the soil's physical and chemical characteristics and climatic conditions. The availability of study results through a web-based dashboard encourages field scale implementation of cropping patterns by the farmers and the participation of other stakeholders. Seven major crops from the Muzaffarnagar district in Uttar Pradesh (India) are selected to demonstrate the proposed approach. The main objectives include 1) identification of major crops and corresponding criteria for their cultivation and evaluating their weights using hybrid system approach, 2) generating thematic layer maps followed by generation of land suitability maps specific to each of the seven major crops using food and agriculture organization (FAO) classification system, and 3) identifying optimum crop rotation pattern required for sustaining soil fertility, maintaining water quality and quantity, and enhancing farmers income. Moreover, the proposed approach’s future development and universal applicability are also discussed.

4.2 Materials and Methods

4.2.1 Study Area

This chapter considers study area as the Muzaffarnagar district in Uttar Pradesh, India which covers an area of about 2960 sq. km. The district is surrounded by River Ganges to its east and by River Yamuna through its western part. It is a land of high fertility with wheat, rice, and sugarcane being its principal crops. The geographic location of the district covers north latitudes from 29° 10’ 49.33” to 29° 42’ 33.33” and east longitudes from 77° 23’ 10.06’’ to 78° 08’ 13.18’’ (Fig. 4.1). The district has about 2200 sq. km. of net sown area with an entire area being irrigated through various sources such as tube wells, canals, etc. and is known for its sugar and jaggery production and has a total of 11 major sugar mills along with steel and paper being its major industries (UPG, 2021). The majority of population i.e., more than 70% is employed in agriculture. Also, Muzaffarnagar has Uttar Pradesh’s biggest granary contributing maximum to Uttar Pradesh’s agricultural Gross Domestic Product (GDP). The massive sugarcane cultivation in the region has resulted in overextraction of groundwater and has contaminated the groundwater quality despite of reasonable average annual rainfall (870 mm).

Owing to general tendency of the farmers to grow sugarcane year after year to obtain maximum income, its over cultivation has degraded the soil fertility. According to the reports (PTI, 2021a, 2021b), farmers are growing sugarcane on 90% of the lands, such high production is becoming even difficult to manage for the mill owners, causing the excess sugarcane crop laid on tractor-trollies dry in sunlight. The high production than the demand is also causing stagnancy in sugarcane prices. These issues have prompted the authors to select this study area. The chapter aims to provide farmers with cost-effective potential solution based on cultivation of different crops or implementing crop rotation practices for healthily confronting the present challenges. The commencement of sustainable crop rotation planning framework involves collection of crop-land suitability parameters i.e., the parameters required for determining land suitability patterns for different crops and the selection of major crops from the study area. The major crops from the study area are selected based on the goals set-out for the crop-rotation planning. The maximization of income return (MIR), and minimization of irrigation water requirement (MIWR) are the two major goals of this study.

Next, the integrated application of SPC, GIS, and collection of in-situ and the remotely sensed datasets under hybrid system approach yields land suitability map specific to each crop. Finally, using the constraint optimization considering MIR and MIWR as two objectives and the cultivable land area as staged by the selected crop-rotation sequences as constraints, the sustainable crop-rotation pattern for the study area is determined. Prominently, the implementation of crop rotation practices entails estimation of strengths and weaknesses of land, assessment of weather conditions for the corresponding land. And contrasting the crop's nutrient, climate, and terrain requirements for the crops under selected crop-rotation sequences with the selected land (Mohler et al., 2009). The complete stepwise procedure for discerning the crop sequence pattern is summarized in Fig. 4.2.

4.2.2 Database curation for the study

Soil's physical and chemical properties have a great influence on crop yields. They directly influence the agrarian activities like erosion, tillage, irrigation, and drainage (Rogers et al., 2015). In general, 17 elements are regarded essential for plant growth and based on their high or low quantitative requirements by the crops, these elements are classified as macronutrients and micronutrients respectively (Parikh et al., 2012). Zolekar and Bhagat (2015) and Dedeo˘glu and Dengiz (2019) are two related studies which have used soil properties for determining land suitability. The detailed information on how these properties influence crop's metabolism events can also be found in these related articles. Both categories of soil nutrients viz., macronutrients and micronutrients, are essential for plants' metabolism events. However, micronutrients are not considered in the present study except for rice, as zinc deficiency has been reported as a widespread issue by many studies particularly for the rice grown in flooded conditions (Wissuwa et al., 2006). The exclusion of the micronutrients owes to the various limitations related to their field-scale applicability, such as lack of subsidies and high goods and services tax on micronutrients as compared to macronutrients, lack of technical knowledge related to micronutrients at field level, limited soil testing facilities (Shukla et al., 2020), and dearth of knowledge or the active research for understanding micronutrients dynamics and transformations under different agricultural productions systems, understanding various biological and physiochemical properties of soil

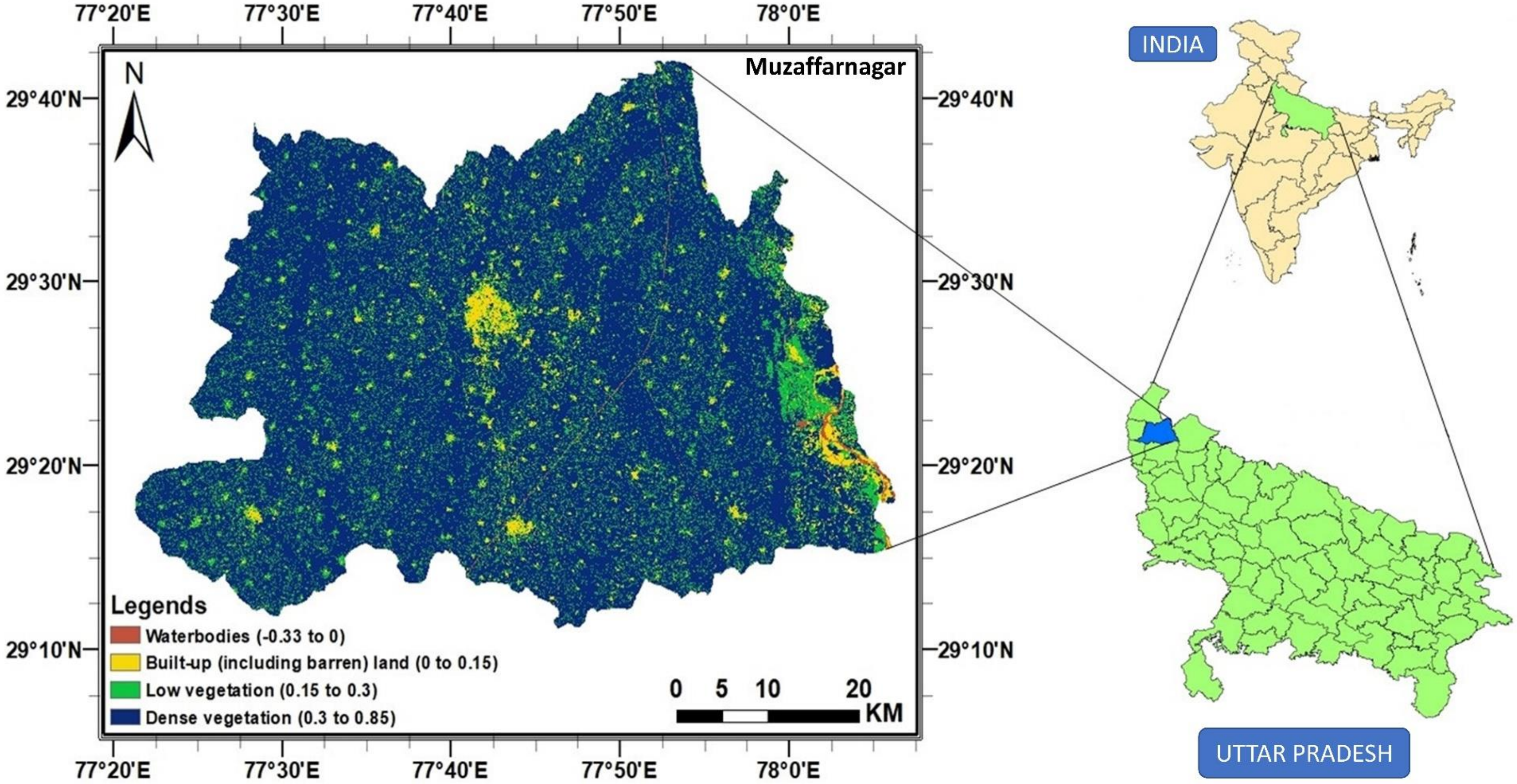


Fig. 4.1 Land use land cover classification of the Muzzafarnagar district (Uttar Pradesh) using NDVI for the year, 2020.

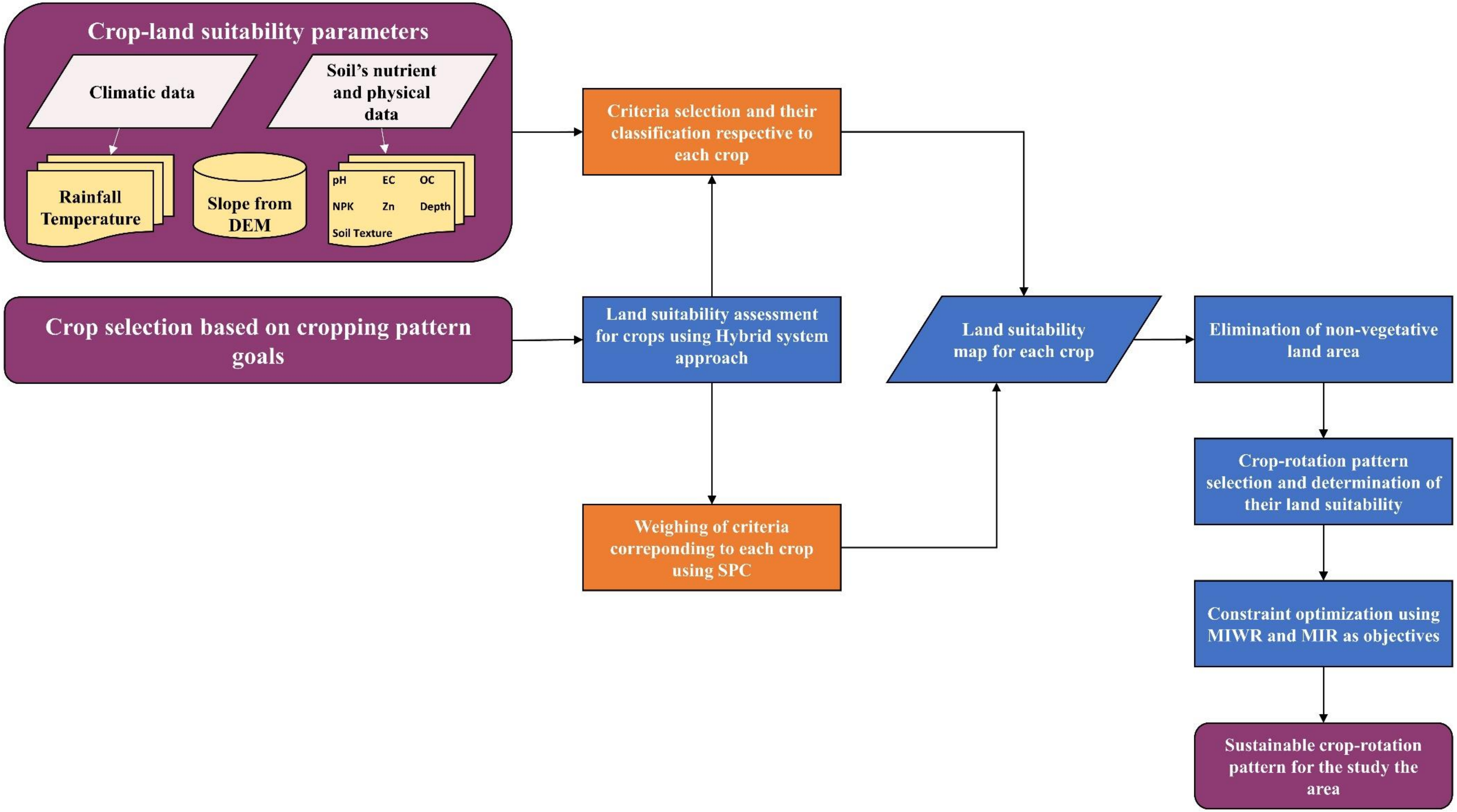


Fig. 4.2 Schematic representation of the adopted methodology for sustainable crop-rotation pattern estimation.

which affect micronutrients' uptake, utilization, and availability (Wang et al., 2016; Nadeem and Farooq, 2019). The physical and chemical properties of soil, and the data concerning climatic conditions for the Muzaffarnagar district is obtained from various in-situ based, remotely sensed geodatabases. The in-situ collection of soil's macro-nutrient and physical parameters e.g., Nitrogen (N), Phosphorus (P), Potassium (K), pH, Electrical conductivity (EC), etc. from 15-20 cm. depth were used for preparing thematic layers for land suitability estimation. These parameters were obtained for Muzaffarnagar district for the selected points (Fig. 4.3), for 2017-2018 to 2018-2019 cycle from Ministry of Agriculture & Farmers Welfare's (Government of India) Soil Health Card initiative (SHC, 2021).

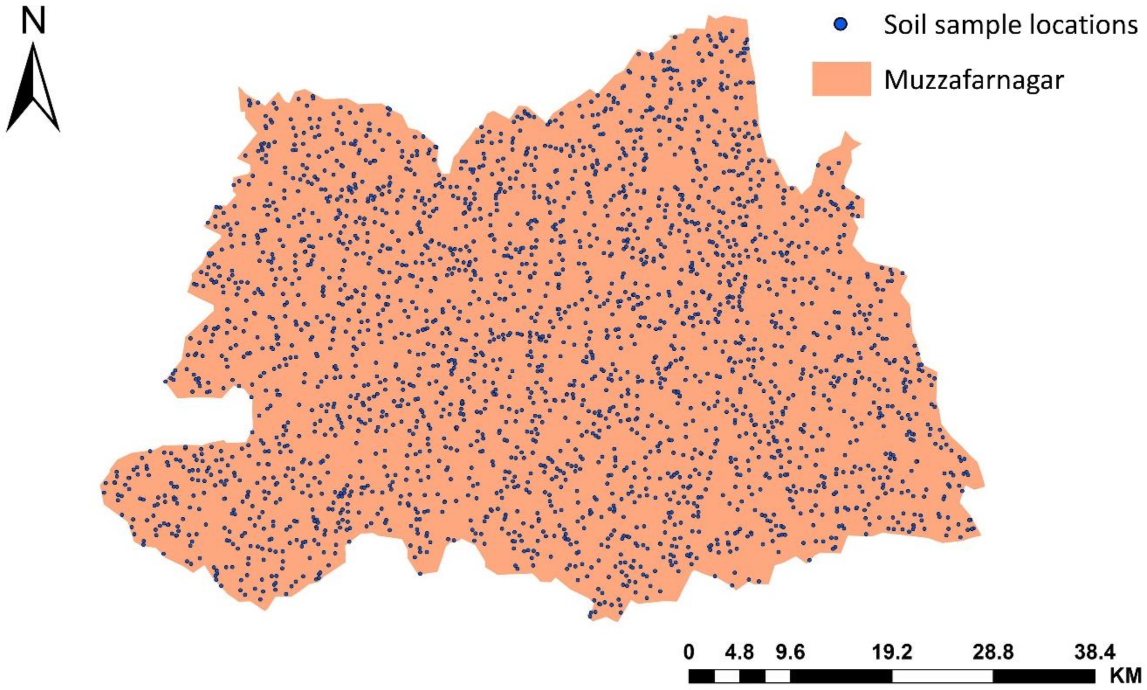


Fig. 4.3 Location for 2700 soil sampling points in the study watershed.

The bulk density layer map for 15-30 cm depth and the soil depth information for the selected area was accessed from International Soil Reference and Information Centre (ISRIC) – World Soil Information (ISRIC, 2021) for standardization of soil macronutrient data. The consideration of soil depth is crucial for certain crops like sugarcane as it requires about 90 cm of soil depth for its healthy growth. However, for almost entire study area, the study the bulk density curves, did not reveal presence of any bedrocks until 200 cm. soil depth. This implies that there is sufficient available soil depth for all the considered crops and therefore, depth as a land suitability parameter (Table 4.2) has not been included while creating crop land suitability maps. The 30-year monthly annual average precipitation data from January 1990 to December 2019 averaged over the months of two cropping seasons i.e., Rabi

(October to April) and Kharif (May to October) is retrieved from the National Aeronautics and Space Administration's Prediction of Worldwide Energy Resource data access platform (NASA, 2021). From the same source, average air temperature 2 meters above the earth surface is attained, the data obtained for random uniformly distributed points were interpolated using ArcGIS.

Further, the soil texture classification layer maps for the study region were created using Editor tool in ArcGIS from the soil texture classification maps published by National Bureau of Soil Survey and Land Use Planning (NBSS, 2021) and from a ground water management report disseminated by Central Ground Water Board, Northern Region, Lucknow (CGWB, 2018). The CartoDEM: Version-3 tiles acquired from Bhuvan Geo Portal & Web Services Group (BGWSG), National Remote Sensing Centre (ISRO, 2021) were merged in ArcGIS and the DEM obtained was used for preparing the slope map layer for the study area. Lastly, the cloud-cover corrected Sentinel-2A satellite images for the year 2020 were obtained using United States Geological Survey's Earth Explorer platform (USGS, 2021) for preparing Normalized Difference Vegetation Index (NDVI) maps for identifying the cultivable land area of the selected region. The NDVI values ranging from -0.33 to 0; 0 to 0.15; 0.15 to 0.3; and 0.3 to 0.85 were used to assign waterbodies, built up, low vegetation, and dense vegetation for the study watershed (Fig. 4.1). Table 4.1 summarizes the datasets, time period, and sources used in developing the crop-rotation planning framework.

Table 4.1 Summary of the dataset used for development of crop-rotation planning framework

Data used	**Source**	**Time period**
Sentinel-2A satellite images	(USGS, 2021)	2020
Soil's macro-nutrient and physical parameters	(SHC, 2021)	2017-18 to 2018-19
Bulk density & Soil depth	(ISRIC, 2021)	2021
Precipitation & Temperature	(NASA, 2021)	Jan. 1990 to Dec. 2019
Soil Texture classification	(NBSS,2021) (CGWB,2018)	2018
DEM	(ISRO, 2021)	2021

4.2.3 Criteria selection, classification, and thematic layers preparation

The chapter uses a hybrid system approach to select the criteria vital for cultivation of selected crops. In this approach, two model types i.e., quantitative and qualitative are assembled for land evaluation (De la Rosa and van Diepen, 2002). We have consulted several stakeholders and agronomy experts from ICAR, CPCB, Department of Irrigation and their qualitative opinions have been used in the model. As a result of hybrid system approach, crucial parameters under land's physical and chemical properties and climatic variations categories such as pH, EC, soil texture, N, P, K, rainfall, and temperature etc. are selected for each crop under consideration as delineated in Table 4.2. The exclusion of Depth (a soil physical property) for the potato crop could be explained as the potatoes have relatively shallower rooting system (beginning with 30 cm.) and are relatively resilient to soil erosion caused by runoff water (high sloping lands). Additionally, potatoes do not typically require saturated or flooded water condition and are grown in properly drained soil environments. On the other hand, mustard is a drought tolerant, climatically adaptable, and a short span growth cycle crop making it less water sensitive and demanding crop. Though, soil texture is an important measure for Sorghum, the deep rooting system requirements, high adaptability, and drought tolerance make soil texture a relatively less sensitive parameter as compared to slope and depth. Hence, slope and depth have been included as potential parameters for evaluating Sorghum crop land suitability. Similarly, other observations concerning land suitability parameters for crops could be explained.

Table 4.2 Land suitability parameters for each crop

Crop type	Land's physical properties	Land's chemical properties	Climatic properties
Paddy	Texture, Slope	pH, EC, N, P, K, OC, Zn	Temperature, Rainfall
Wheat	Texture, Slope	pH, EC, N, P, OC	Temperature, Rainfall
Maize	Texture, Slope	pH, EC, P, K, OC	Temperature, Rainfall
Mustard	Texture, Slope	pH, EC, N, P, K, OC	Temperature
Potato	Texture	pH, EC, OC	Temperature, Rainfall
Sugarcane	Texture, Slope	pH	Temperature, Rainfall
Sorghum	Slope, Depth	pH, EC, N, P, OC	Temperature, Rainfall

Four classes are created for each criterion based on land evaluation classification system as exercised by food and agriculture organization (FAO), United Nations. These classes are S1 (highly suitable), S2 (moderately suitable), S3 (marginally suitable), and N (not suitable) for each of the selected crops. Further, the application of quantitative modelling is achieved by applying stochastic pairwise comparison for each crop which determines the relative weights of each criterion in terms of their importance in cultivation of the crop under discussion. Based on the classification system and curated database (discussed earlier), thematic maps were prepared using ArcGIS (version 10.9) for each criterion specific to each crop type. The raster maps for each criterion were generated by interpolating and masking the point data through instrumentality of Kriging interpolation technique in GIS. Thus, the thematic layers for criteria were prepared by classifying and standardizing prepared raster maps in to four suitability criteria specific to each crop by using raster calculator tool in GIS environment. The importance or the score for each class (i.e., S1, S2, S3, and N) is established through conventional AHP technique. The resultant eigenvector weights with reasonable consistency ratio i.e., $0.06 < 0.1$ were 0.5666, 0.2674, 0.1667, and 0.0399 corresponding to S1, S2, S3, and N class respectively.

4.2.4 Weighting of Criteria using Stochastic approach

Stochastic pairwise comparison propounded by Cobuloglu and Büyüktahtakın (2015) is used in this study to identify the relative weightages of parameters suitable for each crop. To convert DM's valuation to a crisp value, a closed-form approximation of median for the β-distribution is used. The novelty of this approach is that instead of accepting only a single numeral from the experts when comparing two criteria vital for crop growth, this approach provides flexibility to the experts to present their opinion either in form of a 'range of values' or 'most probable value with a lower and a upper bound' or a 'crisp comparison'. Further, SPC deals with the uncertainty or imprecision associated with DM's choice by modelling uncertain comparisons to stochastic pairwise distributions. The approach terminates with successful consistency attainment in pairwise comparison matrix. A detailed stepwise description of this approach is as follows:

- Construction of pairwise comparison matrix specific to each crop: DM performs comparison through crisp response, most probable values with lower and upper bounds or with a range of values. For instance, according to qualitative model, for potato cultivation, soil pH is moderately more important than organic content in the soil; then the score will be P_{po} = 3; if judgement says that temperature is either equally or moderately more important than slope for rice cultivation, then the input will be R_{ts} = (1,3); or in case of wheat, the texture is at least in between equally and moderately important, most likely it's in between moderately and strongly important, or at most strongly more important than pH, then we will obtain W_{tp} = (2,4,5).

- Stochastic pairwise comparison values are converted into crisp values: If 'l' and 'm' to be the two criteria related to crop A and the crisp value for the corresponding pairwise comparison equal to A_{lm}. And let $G_{lm}(A_{lm}|\Phi_{lm})$ be the probability density function with parameters Φ_{lm} for converting stochastic comparison values to crisp. Following the previous step, for example, W_{tp} = {2,4,5} can be modelled using a triangular distribution with lower limit (ll), most likely (ml), and upper limit (ul) as $W_{tp} \sim G_{tp}$ (ll, ml, ul) = t_{tp} (2,4,5). Similarly, R_{ts} = {1,3} can be modelled using a uniform distribution function, $R_{ts} \sim G_{ts}$ (ll, ul) = u_{ts} (1,3) and the direct crisp comparisons are simply written as $Ppo \sim G_{po} = 3$. For standardization of different distributions, a pairwise β-distribution function is used, β(Θ|υ, ω, ll, ul) where Θ is beta-distributed pairwise comparison value, (υ, ω) are the shape factors, and (ll, ul) are the location parameters, with $ll \leq \Theta \leq ul$ and $\upsilon, \omega \geq 1$.

  The methods of moments are used to model all A_{lm} to β-distributed functions with shape factors (υ_{lm}, ω_{lm}) and location parameters (ll_{lm}, ul_{lm}). First, using the first and the second moment sample mean and variance [A_{lm}] is calculated.

$$E[\tilde{A}] = ll + \frac{\upsilon}{\upsilon+\omega}(ul - ll) \tag{4.1}$$

$$Var[\tilde{A}] = \frac{\upsilon\omega}{(\upsilon+\omega)^2(\upsilon+\omega+1)}(ul - ll) \tag{4.2}$$

where,

$$E[\tilde{A}] = \frac{ll+ml+ul}{3}\text{, and} \tag{4.3}$$

$$Var[\tilde{A}] = \frac{\mathrm{ll}^2+\mathrm{ml}^2+\mathrm{ul}^2-ll\,ml-ll\,ul-ml\,ul}{18} \tag{4.4}$$

Equating Eqs. (4.1) & (4.2) to Eqs. (4.3) & (4.4) respectively, υ (Eq. 4.5) and ω (Eq. 4.6) are obtained as follows,

$$\upsilon = \left(\frac{E[\tilde{A}]-ll}{ul-ll}\right)\left(\frac{\left(\frac{E[\tilde{A}]-ll}{ul-ll}\right)\left(1-\left(\frac{E[\tilde{A}]-ll}{ul-ll}\right)\right)}{Var[\tilde{A}]/(ul-ll)^2}-1\right) \tag{4.5}$$

$$\omega = \left(1-\frac{E[\tilde{A}]-ll}{ul-ll}\right)\left(\frac{\left(\frac{E[\tilde{A}]-ll}{ul-ll}\right)\left(1-\left(\frac{E[\tilde{A}]-ll}{ul-ll}\right)\right)}{Var[\tilde{A}]/(ul-ll)^2}-1\right) \tag{4.6}$$

The outputs for conversion of stochastic to β-distributed pairwise comparison after applying methods of moments (MoM) are as mentioned below:

$$\Theta_{lm} \sim \beta(\upsilon_{lm}, \omega_{lm}, ll_{lm}, ul_{lm}) \text{ if } A_{lm} \sim t(ll_{lm}, ml_{lm}, ul_{lm}) \tag{4.7}$$

$$\Theta_{lm} \sim \beta(\upsilon_{lm} = 1, \omega_{lm} = 1, ll_{lm}, ul_{lm}) \text{ if } A_{lm} \sim u(ll_{lm}, ul_{lm}) \tag{4.8}$$

$$\Theta_{lm} = A_{lm} \text{ if } A_{lm} \text{ is crisp} \tag{4.9}$$

For detailed study on conversion of stochastic pairwise comparison to β-distributed pairwise comparison user may refer Jalao et al. (2014).

- The closed-form approximation as developed by Kerman (2011), is used to convert β-distributed pairwise comparison to crisp values. The crisp value is obtained using median of β-distribution (Eq. 4.10),

$$M(\upsilon_{lm}, \omega_{lm}) \approx \frac{\upsilon lm - 1/3}{\upsilon lm + \omega lm - 2/3} \tag{4.10}$$

subjected to,

$$\frac{\upsilon lm - 1}{\upsilon lm + \omega lm - 2} \leq M(\upsilon_{lm}, \omega_{lm}) \leq \frac{\upsilon lm}{\upsilon lm + \omega lm} \tag{4.11}$$

Equation 4.10 is applicable for the cases when $\upsilon_{lm} \geq \omega_{lm}$, elsewise the inequalities would get reversed. Lastly, the crisp value (Eq. 4.12) for Θ_{lm} is attained using the formula as mentioned below:

$$\Theta_{lm} = ll_{lm} + M(\upsilon_{lm}, \omega_{lm}) * (ul_{lm} - ll_{lm}) \tag{4.12}$$

After constructing pairwise comparison matrix for all criterions, the weightage or value of each criterion for supporting the growth of a particular crop is calculated using priority eigenvector followed by consistency evaluation.

4.2.5 Predicting sustainable crop rotation pattern

The criteria weights and the respective thematic map layers with four classified intervals for a particular crop were overlaid in ArcGIS to obtain suitable land pattern for each crop. The resulted crop-land suitability maps were then overlaid with NDVI map for the year, 2020 to produce crop-land suitability maps suggesting the suitable land only for the region which supports vegetation i.e., the areas with built-up land and waterbodies were eliminated. The resulted crop-suitability land areas were further used for estimating optimal crop rotation pattern based on the two objectives i.e., maximization of income returns and minimizing irrigation water requirements. The constraint optimization (CO) has been applied upon the selected set of cropping patterns. The detailed information of irrigation water requirements (IWR) and net income return (NIR) for each cropping pattern is mentioned in Table 4.3. The IWR and NIR for the cropping patterns have been deduced using the individual crop's water requirement, production, production cost, and market cost price information (DAC, 2019; DES, 2012; FAO, 1986; MAFW, 2018). The information related to these computations has been included in the Appendix-A (Tables A11 and A12). These cropping patterns are the different possible combinations of the seven selected crops and are obtained through past agricultural experiences of the study area, experts' consent, and detailed literature surveys (Chandrasekaran et al., 2010; DSD, 2013; Parihar et al., 2011). In addition, the cropping patterns corresponding to each objective were also estimated for facilitating a flexible selection of cropping pattern to addressing subjective needs of the farmers.

Table 4.3 Crop-rotation patterns and corresponding information on Irrigation Water Requirements and Net Income Return

Sr. No.	Crop-rotation patterns	Irrigation Water Requirements (mm/annum)	Net Income Return (₹/hectare/annum)
1	Rice-Wheat-Fallow	750	28189.00
2	Maize-Wheat-Fallow	800	22167.33
3	Maize-Potato- Maize-Wheat-Fallow	980	48470.40
4	Maize-Mustard-Fallow	700	21464.80
5	Sorghum-Mustard-Fallow	633.33	66177.47
6	Sorghum-Wheat-Fallow	733.33	23878.67
7	Rice-Mustard-Fallow	650	28486.47

Sr. No.	Crop-rotation patterns	Irrigation Water Requirements (mm/annum)	Net Income Return (₹/hectare/annum)
8	Rice-Wheat-Sugarcane-Fallow	1562.5	68108.25
9	Maize-Wheat-Sugarcane-Fallow	1600	62842.00
10	Rice-Potato-Sugarcane-Wheat-Fallow	1490	85485.40
11	Rice-Mustard-Sugarcane-Wheat-Fallow	1410	63194.28
12	Rice-Wheat-Sugarcane-Wheat-Fallow	1470	63615.80
13	Rice-Potato-Maize-Potato-Fallow	970	74553.00
14	Maize-Potato-Sugarcane-Fallow	1625	90179.00

Sources: (DAC, 2019; DES, 2012; FAO, 1986; MAFW, 2018)

4.3 Results & Discussion

This chapter suggests sustainable crop rotation planning for the Muzaffarnagar district for addressing the daunting issues of declining water quality and quantity, which is in fact a consequence of excessive cultivation of sugarcane and paddy-wheat rotations (Tyagi et al., 2009; Umar et al., 2006). The sustainability aspects of environment such as improving fertility, reducing usage of chemical fertilizers, and economic well-being of the farmers are other contributing factors for deciding appropriate crop planning sequence. Seven major crops of the study region viz. wheat, paddy, sugarcane, maize, mustard, sorghum, and potato were selected for addressing the aforesaid issues. Parallelly, as per Fig. 4.2, the database concerning soil's physical and chemical properties: pH, EC, OC, N, P, K, texture, depth; weather and topography conditions: rainfall, temperature, and slope is curated as discussed in the previous section. The criteria selection for the seven selected crops is accomplished through the application of the 'Hybrid system approach'. The list of criteria with suitability classification S1 (highly suitable), S2 (moderately suitable), S3 (marginally suitable), and N (not suitable)) for rice and wheat crop are provided in Tables 4.4 and 4.5. Subsequently, the classified thematic layers for each criterion corresponding to each crop were prepared using the land suitability parameters (Fig. 4.4) and the criteria weights using ArcGIS.

Table 4.4 Suitability range for criteria corresponding to rice crop

Land suitability parameters ↓	**S1**	**S2**	**S3**	**N**
Suitability class score →	**0.5667**	**0.2674**	**0.1667**	**0.0399**
Temperature (°Celcius)	25 to 30	30 to 35	10 to 20	<10 and >35
pH	5.5 to 7.5	7.5 to 8 5 to 5.5	8 to 8.5 4.5 to 5	>8.5 <4.5
Precipitation (mm)	>1500	1000 to 1500	700 to 1000	<700
Electrical Conductivity (dS/m)	<3	3 to 5	5 to 7	>7
Soil Texture	Loam, Sandy clay, Sandy loam, Loamy and, Clay	Sandy Clay, Silty loam, Silty clay	Silt, Clay, Silty clay	Gravel, Sand
Slope (%)	<1	1 to 2	2 to 6	>6
Nitrogen (ppm)	>80	80 to 40	40 to 20	<20
Phosphorus (ppm)	>15	15 to 10	10 to 5	<5
Potassium (ppm)	>400	400 to 200	200 to 100	<100
Organic Carbon (%)	>2	2 to 1	2 to 0.5	<0.5
Zinc (ppm)	>1	1 to 0.5	0.5 to 0.25	<0.25

Table 4.5 Suitability range for criteria corresponding to wheat crop

Land suitability parameters ↓	**S1**	**S2**	**S3**	**N**
Suitability class score →	**0.5667**	**0.2674**	**0.1667**	**0.0399**
Temperature (°C)	15 to 18.5	18.5 to 19.5	19.5 to 21.5	>21.5
		15 to 14.5	14.5 to 12.5	<12.5
pH	6.5 to 7.5	7.5 to 8.2	8.3 to 8.5	>8.5
		6.5 to 5.5	5.5 to 5.2	<5.2
Precipitation (mm)	450 to 650	650 to 850	850 to 1500	>1500
		450 to 350	350 to 250	<250
Electrical Conductivity (dS/m)	<3	3 to 5	5 to 10	>10
Soil Texture	Clay, Silt, Silty clay, Silty loam, Sandy clay	Loam, Clayey loam, Silty clay	Sandy Clay, Sandy loam	Loamy sand, Sand
Slope (%)	<8	8 to 18	18 to 35	>35
Nitrogen (ppm)	>2000	1500 to 2000	1000 to 1500	<1000
Phosphorus (ppm)	>10	5 to 10	3 to 5	<3
Organic Carbon (%)	>3	3 to 2.5	2.5 to 1	<1

4.3.1 Application of Stochastic pairwise-comparison approach

This section describes the application of quantitative modelling component under Hybrid system approach taking paddy crop as an example to determine the relative weights of the soil properties, topography, and weather criteria. A total of 11 parameters are considered and group of agronomy experts and farmers are consulted for providing either a range of values or the most probable values or a crisp number for pairwise comparison of parameters concerning the crops under discussion. The judgement of experts (comparison matrix) for paddy crop are summarized in Table 4.6.

Table 4.6 Stochastic pairwise comparison matrix for the paddy crop

Parameter	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
Temp. (C1)	1	U(1,3)	U(1,3)	T(2,3,4)	T(2,3,5)	U(1,3)	U(1,3)	T(2,4,5)	T(2,3,4)	T(2,4,5)	T(2,3,4)
pH(C2)		1	Ǔ(5,4)	T(1,2,3)	Ť(6,4,3)	Ť(7,4,3)	U(2,3)	(3)	(3)	(3)	(3)
Rain(C3)			1	T(2,3,4)	T(2,3,4)	(3)	(2)	T(2,3,5)	T(2,4,5)	T(2,3,4)	T(2,3,5)
EC(C4)				1	Ť(6,5,3)	Ť(6,5,3)	T(2,3,4)	T(3,4,5)	T(3,4,6)	T(3,4,7)	(4)
Text.(C5)					1	U(2,3)	U(1,2)	(3)	(3)	(3)	U(3,4)
Slope(C6)						1	U(2,3)	(4)	(4)	(4)	U(4,5)
N(C7)							1	(3)	(3)	(3)	U(3,4)
P(C8)								1	(1/2)	(1/2)	(1)
K(C9)									1	(1)	(2)
OC(C10)										1	(2)
Zn(C11)											1

NOTE: Ǔ and Ť are inverse of U and T (Example: T(1/6,1/4,1/3) = Ť(6,4,3))

This comparison matrix (Table 4.6) is converted to β-distributed pairwise comparison using equations 4.7 to 4.9; the resulted matrix is given in Table 4.7. The weights, based on the crisp comparison matrix, are derived by identifying the normalized priority eigenvector (Thomas L. Saaty, 1980) and ensuring the consistency of the matrix through consistency ratio index. The relative weights of the parameters for the paddy crop cultivation as resulted from the stochastic pairwise comparison approach is rendered in Table 4.9. Finally, the matrix with crisp comparison is obtained using equations 4.10 to 4.12 as represented in Table 4.8.

Thus, temperature (17.45%), rainfall (16.94%), soil texture (13.16%), and slope (13.51%) are observed to be the major parameters influencing paddy crop cultivation followed by electrical conductivity (9.32%) and pH (8.42%). These results are consistent with the findings of (Amini et al., 2020; Ujoh et al., 2019), where they have used conventional AHP approach which lacks stochastic comparison of alternatives and also provides less flexibility to the decision makers as compared to the approach adopted in this study. In case of inconsistency within the comparison matrices (i.e., CR > 0.1; Saaty, 1980), the matrices were revised. The weights to the criteria corresponding to all other crops were ascribed following the similar procedure. The thematic layers prepared earlier were overlaid with the help of the weights obtained using raster calculator tool in the ArcGIS. Thus, the land suitability maps for all the crops considered in this study are obtained and are presented in Fig. 4.5.

The maps depicted in Fig. 4.5 were then modified by removing the land use classes corresponding to built-up areas and waterbodies in the 2020 NDVI map using raster calculator in ArcGIS. The eliminated area counts only around 2.5% (6,950 hectares) of the total area. Thus, the resulting maps indicates that only 3.5% (9,015 hectares) of land constitutes high suitability for paddy cultivation in Muzaffarnagar while about 26% (67,400 hectares) of land lying mostly in the upper part of the district (i.e., covering portions of Charthawal, Muzaffarnagar, Morna, and Purkazi blocks) supports moderate and 68% (177210 hectares) of the remaining land supports marginal cultivation of the paddy crop. Paddy is a temperature sensitive and water loving crop. It requires more than 1500 mm precipitation and around 25 to 30 degrees Celsius temperature for its optimum growth. However, the highest annual average precipitation being 1050 mm and the high average temperature i.e., more than 29.5 degree Celsius in the study region could be a cause of low high-suitability paddy farming regions. Similarly, the upper portions being rich in precipitation with lower temperatures ranges are more suitable for paddy cultivation than the remaining parts of the district. As the saying goes that Muzaffarnagar is the sugar bowl of India, the results also propound the concurrent statistics with sugarcane having the highest land in comparison to any other crop i.e., 60% (150035 hectares) under high suitability region and about 40% (1,02,341 hectares) under moderate suitability region.

The apposite sugarcane growth requirements encompassing about neutral soil pH (6.5 to 7.5), loamy to sandy loamy soil texture, good soil depth, 20-to-30-degree Celsius temperature, and rainfall greater than 950 mm (ICAR, 2021; Rasheed and Venugopal, 2009) in the study area are the potential factors for the observed trend. Similarly, for the wheat crop 31% (79,823 hectares) land is under high suitability region whereas 66% (1,71,835 hectares) land is under moderate suitable region. These results are congruent with the general observed trend i.e., wheat and sugarcane are the two most suitable crops for the land in Muzaffarnagar with rice being the third principal crop with a quite reduced production as compared to the other two principal crops (KVK, 2015).

However, results of this chapter indicates that potato, maize, and mustard crops also have high cultivation potential in Muzaffarnagar district, around 20% (66,361 hectares) land for mustard, and 25% (64,500 hectares) for both maize and potato lies within high suitability (S1) region with 35% to 45% land moderately good for cultivation of these crops. This is primarily due to the favourable slope (i.e., more than 90% region having slope from 0 to 6%), soil texture (loam and sandy loam), and rainfall conditions (greater than 800mm) for maize (Tashayo et al., 2020); favourable soil texture (loam and sandy loam), and phosphorus content (10 to 55 Kg/hectare) for mustard (Mandal et al., 2020); and texture (loam and sandy-

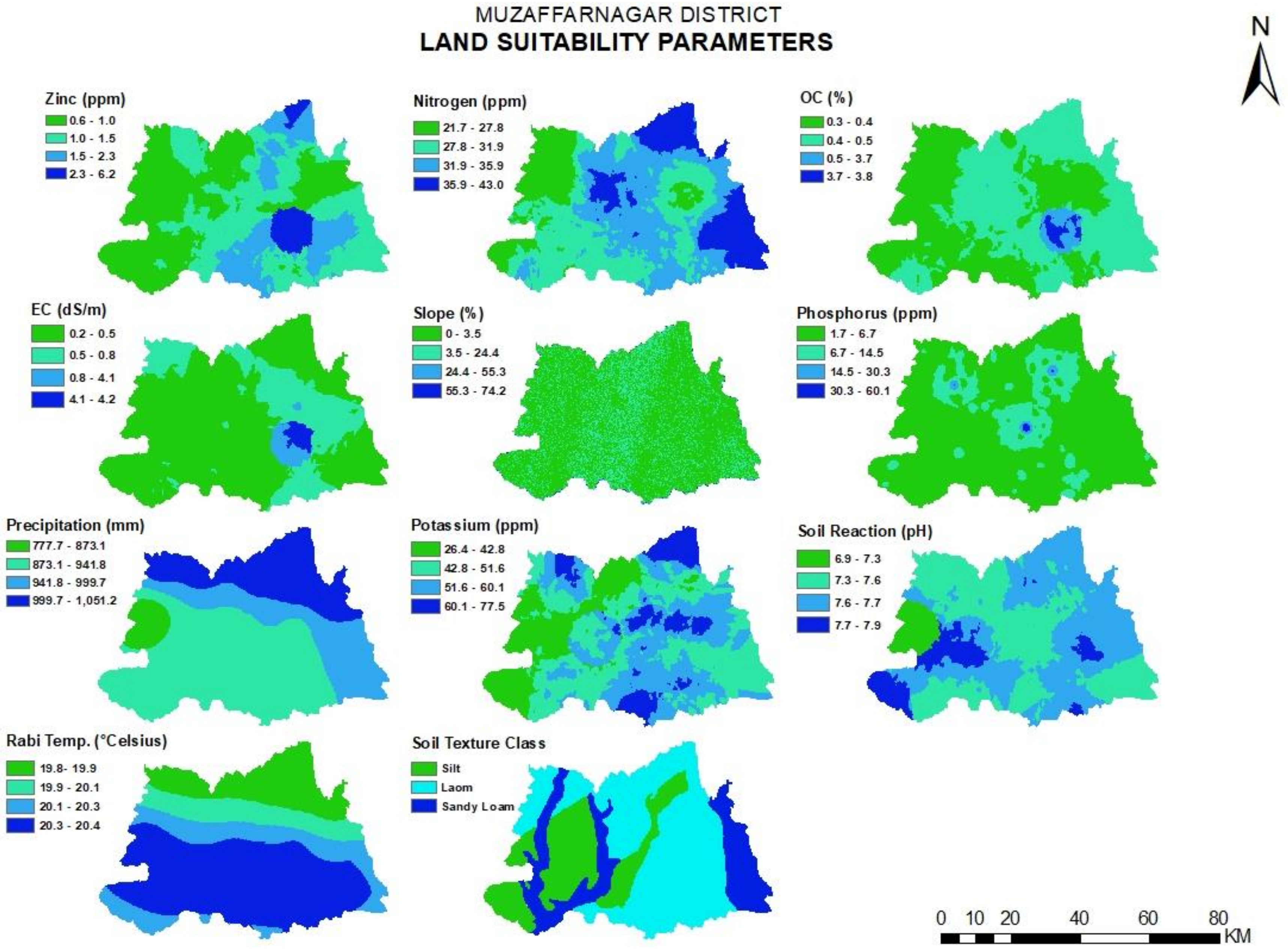


Fig. 4.4 Input parameter maps for generating land suitability patterns for crops.

Table 4.7 β-distributed pairwise comparison matrix for the paddy crop

Parameter	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
Temp.(C1)	1	β(1,1,1,3)	β(1,1,1,3)	β(2.5,2.5,2,4)	β(2.1,2.2,2,5)	β(1,1,1,3)	β(1,1,1,3)	β(2.6,2.1,2,5)	β(2.5,2.5,2,4)	β(2.6,2.1,2,5)	β(2.5,2.5,2,4)
pH(C2)		1	β(1,1,0.2,0.25)	β (2.5,2.5,1,3)	β(2.5,2.5,1/6,1/3)	β(2.6,2.4,1/7,1/3)	β(1,1,2,3)	3	3	3	3
Rain(C3)			1	β (2.5,2.5,2,4)	β(2.5,2.5,2,4)	3	2	β(2.1,2.6,2,5)	β(2.6,2.1,2,5)	β(2.5,2.5,2,4)	β(2.1,2.6,2,5)
EC(C4)				1	β(1.7,2.5,1/6,1/3)	β(1.7,2.5,1/6,1/3)	β(2.5,2.5,2,4)	β(2.5,2.5,3,5)	β(2.1,2.6,3,6)	β(1.8,2.6,3,7)	(4)
Text.(C5)					1	β (1,1,2,3)	β(1,1,1,2)	3	3	3	β(1,1,3,4)
Slope(C6)						1	β(1,1,2,3)	4	4	4	β(1,1,4,5)
N(C7)							1	3	3	3	β(1,1,3,4)
P(C8)								1	1/2	1/2	1
K(C9)									1	1	2
OC(C10)										1	2
Zn(C11)											1

Table 4.8 Median or crisp pairwise comparison matrix for the paddy crop

Parameters	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
Temperature (C1)	1.00	2.00	2.00	3.30	3.00	2.00	2.00	3.69	3.00	3.69	3.00
pH(C2)	0.50	1.00	0.22	2.00	0.25	0.24	2.50	3.00	3.00	3.00	3.00
Rainfall(C3)	0.50	4.44	1.00	3.00	3.00	3.00	2.00	3.30	3.69	3.00	3.30
EC(C4)	0.30	0.50	0.33	1.00	0.23	0.23	3.00	4.00	4.36	4.60	4.00
Texture(C5)	0.33	4.00	0.33	4.35	1.00	2.50	1.50	3.00	3.00	3.00	3.50
Slope(C6)	0.50	4.12	0.33	4.35	0.40	1.00	2.50	4.00	4.00	4.00	4.50
N(C7)	0.50	0.40	0.50	0.33	0.67	0.40	1.00	3.00	3.00	3.00	3.50
P(C8)	0.27	0.33	0.30	0.2	0.33	0.25	0.3	1.00	0.50	0.50	1.00
K(C9)	0.33	0.33	0.27	0.23	0.3	0.20	0.33	2.0	1.00	1.0	2.0

Parameters	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
OC(C10)	0.2	0.33	0.3	0.22	0.33	0.2	0.33	2.00	1.00	1.0	2.00
Zn(C11)	0.33	0.33	0.30	0.25	0.29	0.22	0.2	1.0	0.50	0.50	1.0

Table 4.9 Land suitability criteria for paddy crop cultivation and corresponding weights

Parameters	Weights	CI	RI	CR
Temperature (C1)	0.1745	0.1500	1.51	0.099342593
pH(C2)	0.0842			
Rainfall(C3)	0.1694			
EC(C4)	0.0932			
Texture(C5)	0.1316			
Slope(C6)	0.1351			
N(C7)	0.0756			
P(C8)	0.0291			
K(C9)	0.0391			
OC(C10)	0.0388			
Zn(C11)	0.0293			

-loam), and rainfall (800 mm or more) are the most favourable conditions for potato cultivation (Mandal et al., 2020; Soni, 2021). Sorghum crop considered in this chapter also has a good cultivation potential in Muzaffarnagar. However, as summarized by agricultural reports, these crops are cultivated in very petite amounts.

Thus, some crops with good cultivation potential are not given due consideration. This can be true because of the lack of land use planning and policies leading to a biased selection of the crops based on subjective suitability of farmers like considering the market or economic aspects alone, which may sustain for some short period of time. But for sustainable agriculture planning or cropping pattern selection, a comprehensive consideration i.e., simultaneous contemplation on ecological, hydrological, economical, and socio-economic aspects is must. For the present study area, sugarcane is the most suitable crop for Muzaffarnagar, thus, naturally has a good market. The lack of proper land use planning and policies has led to extensive cultivation of sugarcane crop and consequently many complications have risen such as overexploitation of the ground water, land degradation, high usage of chemical fertilizers, and thus impairing water quality. According to a report on Ground water management by the Central Ground Water Board, Government of India (CGWB, 2018), the groundwater in 3 blocks (Baghra, Budhana, Charthawal) out of 9 blocks in the Muzaffarnagar district are found to be overexploited with one 1 block (Shahpur) reaching critical state. The sustainable crop rotation planning is the one of the best viable solutions which can take several parameters into account like economic, environmental, agronomical, hydrological etc. while crop rotation planning. The upcoming section illustrates sustainable crop rotation planning for the selected study area.

4.3.2 Sustainable crop rotation planning

This section presents the results of crop-rotation planning for Rabi and Kharif seasons using the seven crops (as discussed above) based on the two objectives, namely, maximization of income return (MIR) and minimization of irrigation water requirements (MIWR). This is accomplished by categorizing the crop-land suitability areas into two classes namely 'suitable land' and 'non-suitable land' for cultivation of crops. The land area under 'S1' and 'S2' region, as depicted in Fig. 4.5, is classified as 'land suitable' and 'S3' land area as 'non-suitable land' for cultivation of crops. Using stakeholder's opinion towards seven selected crops, different agronomically feasible permutations of crop-rotation patterns were formed as summarized in Table 4.3. The 'suitable/non-suitable land' information for each crop is then overlaid and intersect respective to each crop-rotation pattern and the land area suitable for each cropping patterns is thus deduced. Now, a sustainable and optimized crop-rotation pattern is estimated for each land parcel in the entire Muzaffarnagar district using MIR and MIWR objective functions. Additionally, the crop-rotation patterns corresponding to only MIWR and only MIR objective were also suggested to provide flexibility to the farmers and the local authorities for choosing a particular cropping pattern as per the native absolute requirement.

Fig. 4.6 (a) to Fig. 4.6 (c) presents the crop-rotation patterns corresponding to minimization of irrigation water requirement, sustainable or constraint optimization, and maximization of income return scenarios respectively. The annual irrigation water consumption, annual net return, and total acreage corresponding to each cropping pattern for each of the three aforementioned scenarios are summarized in Tables 4.10 - 4.12. The allocation of crops based on above mentioned three scenarios provides substantial benefits like providing a natural pest control system, soil hygiene, enhancement in crop yield, minimizing fertilizer usage, etc., by preventing overexploitation of soil because of excessive cultivation of one crop-type. Eventually, it would preserve soil fertility and prevent water degradation by limiting use of pesticides and insecticides in the field (Bonanomi et al., 2020; CEF, 2021; Hashimi and Hashimi, 2020). In addition to the aforementioned factors, the sustainable or constraint optimized cropping pattern is an attempt to provide maximum and long-term benefit to farmers while simultaneously minimizing water consumption. Essentially, the CO scenario is a trade-off between the two non-complementary or contrasting objectives, MIWR and MIR. Following the results (Table 4.10 to 4.12), the CO scenario provides 50% more income returns on the cost of 30% more water than MIWR scenario. On the other hand, the crop rotation patterns in CO ensues 20% less profit than the maximum profit (MIR) scenario but saves near 40% of water consumed. According to the general agricultural statistics for Muzaffarnagar district as reported by the Department of Land Development and Water Resources (IWMP, 2009) and by the local Krishi Vigyan Kendra for the year 2014, sugarcane, wheat, rice are the principal crops for the studied region. In a gradual incrementing manner, sugarcane cultivation area has increased to more than 90% of the cultivated area, whereas the wheat and paddy are cultivated on around 57% and 10% of the remaining land respectively. Also, the cropping intensity for the district is 153.2%.

While the potato, mustard, maize, sorghum crops account for only 1.5%, 1.8%, 0.1%, and 0% land area. The Fig. 4.7 shows the annual average percentage of the land covered by the different crops under the three different scenarios. The detailed information related to computation of these annual average percentages have been presented in the Appendix-A through Tables A13 and A14. The annual average land use percentages for different crops suggest that even for retrieving maximum profit from the land (i.e., under MIR scenario) which would essentially be at the cost of more water consumption, a maximum of about 20% of land area can be allocated for sugarcane cultivation. Also, as can be inferred from Fig. 4.7, a minimum of 25% of the cultivated land area should be allocated to fallow lands while practicing crop-rotation patterns and for achieving sustainable agriculture. This practice is also not being followed and allocation of less than 5% fallow land is currently practiced.

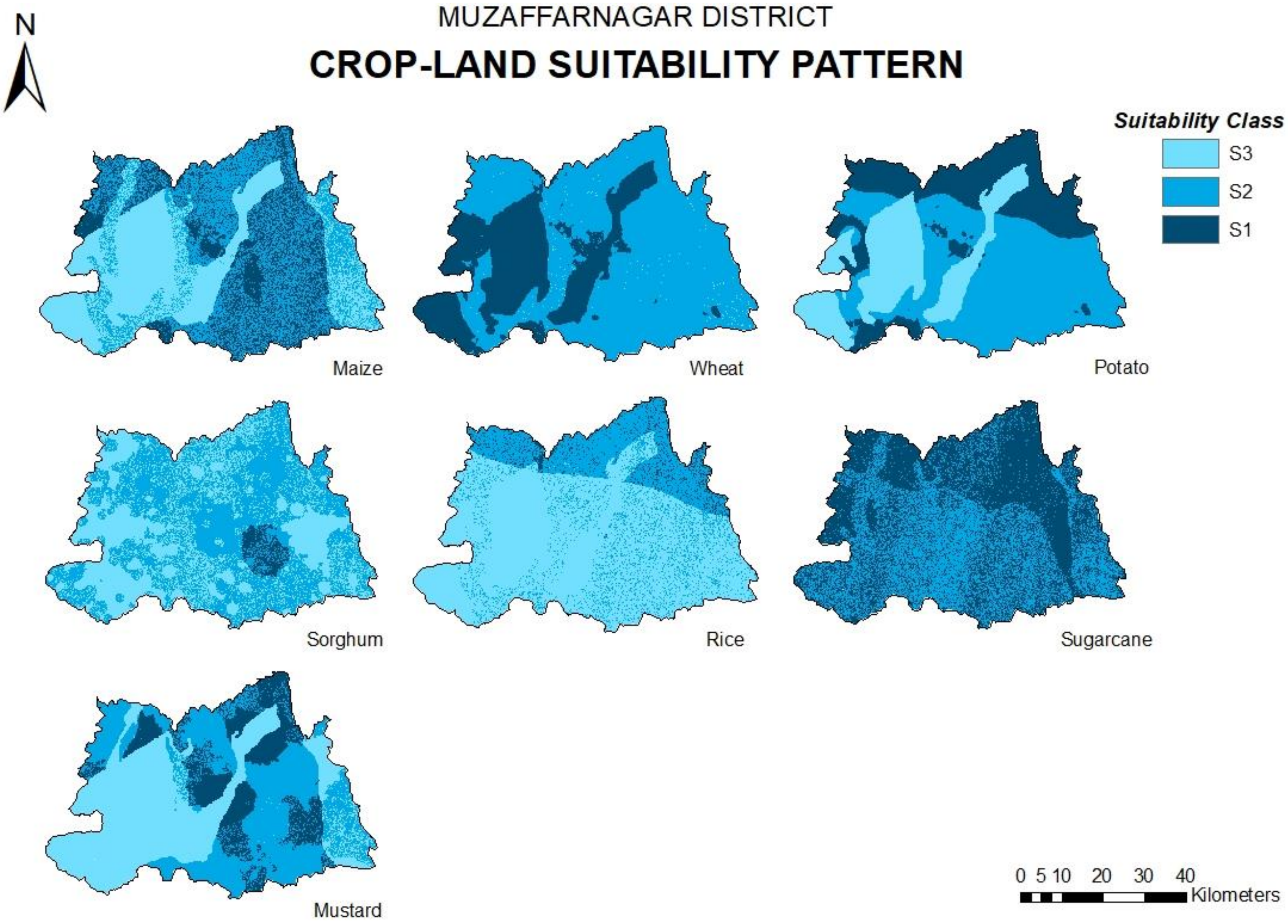
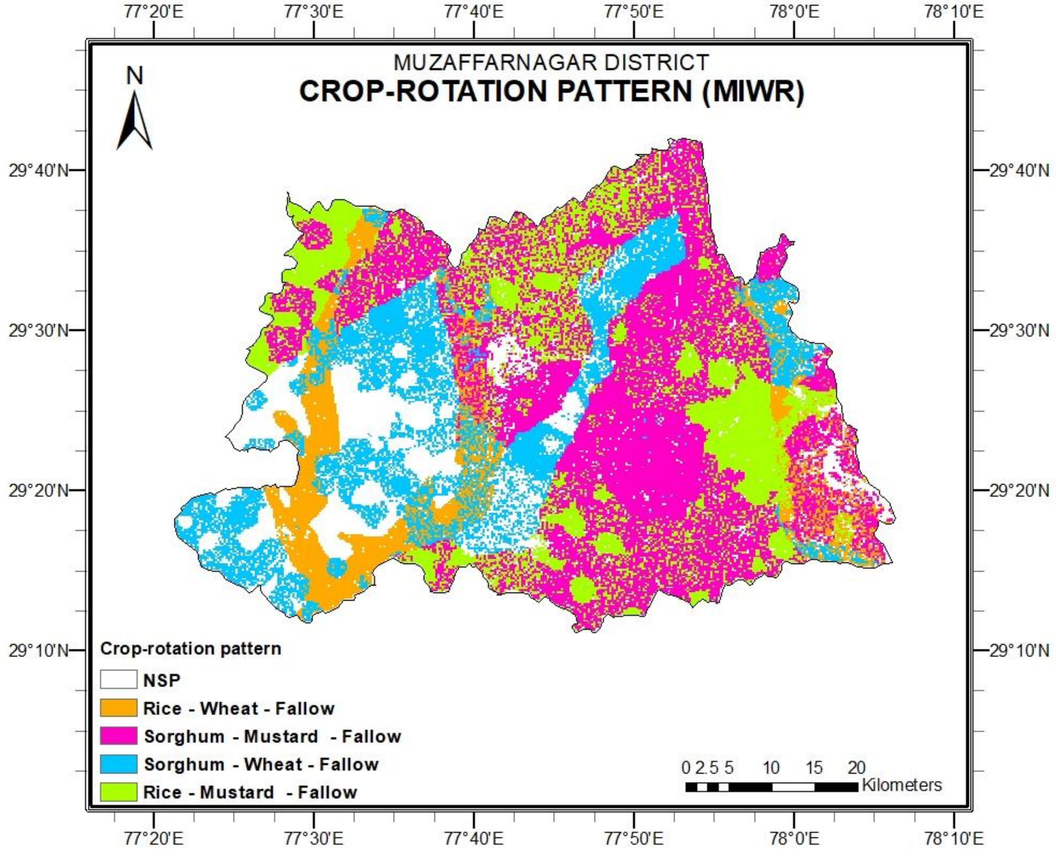
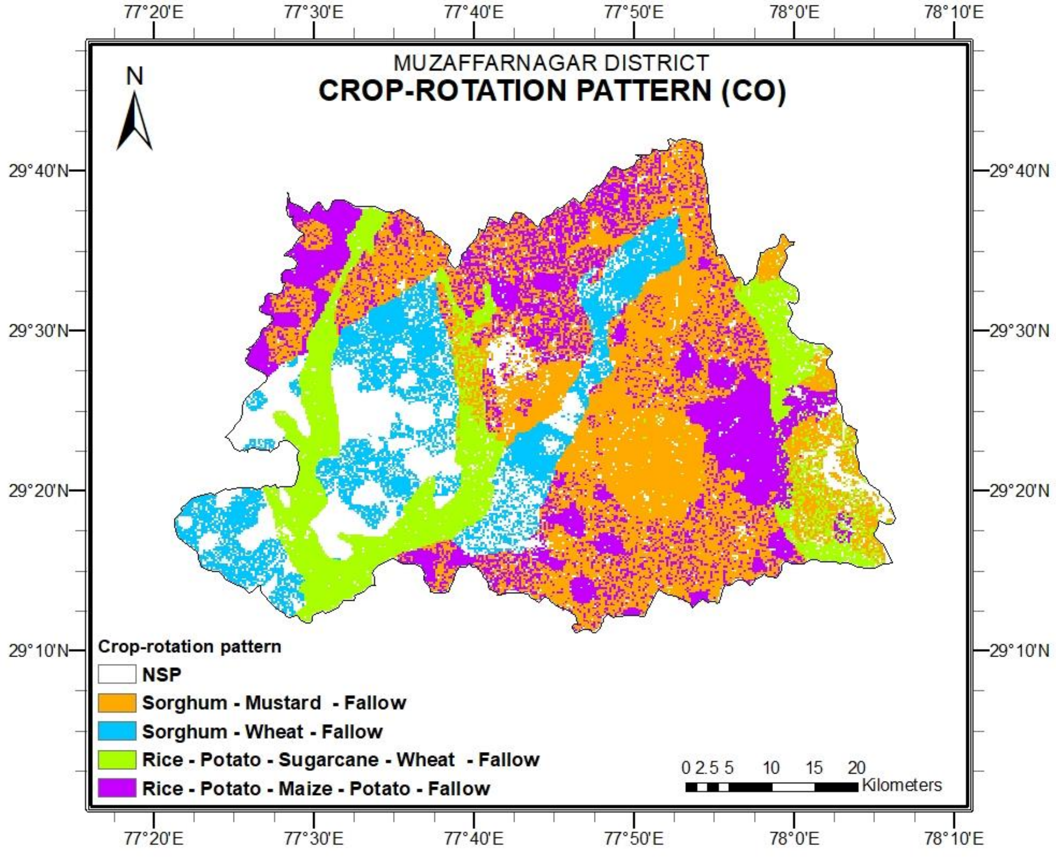


Fig. 4.5 Land suitability maps for crops for Muzaffarnagar district.


MUZAFFARNAGAR DISTRICT
CROP-ROTATION PATTERN (MIWR)
N
Crop-rotation pattern
NSP
Rice - Wheat - Fallow
Sorghum - Mustard - Fallow
Sorghum - Wheat - Fallow
Rice - Mustard - Fallow
0 2.5 5 10 15 20
Kilometers
77°20'E
77°30'E
77°40'E
77°50'E
78°0'E
78°10'E
29°40'N
29°30'N
29°20'N
29°10'N


MUZAFFARNAGAR DISTRICT
CROP-ROTATION PATTERN (CO)
N
Crop-rotation pattern
NSP
Sorghum - Mustard - Fallow
Sorghum - Wheat - Fallow
Rice - Potato - Sugarcane - Wheat - Fallow
Rice - Potato - Maize - Potato - Fallow
0 2.5 5 10 15 20
Kilometers
77°20'E
77°30'E
77°40'E
77°50'E
78°0'E
78°10'E
29°40'N
29°30'N
29°20'N
29°10'N

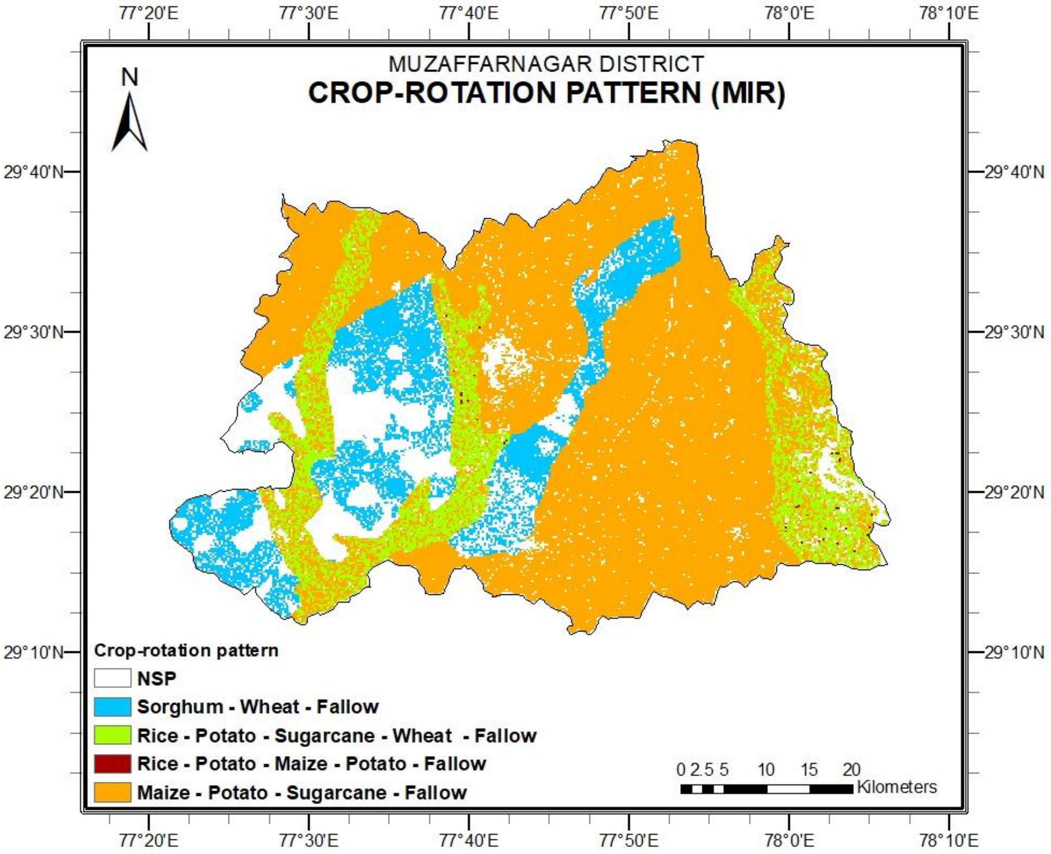


Fig. 4.6 (a) Crop-rotation pattern for Muzaffarnagar district corresponding to minimum irrigation water requirement, (b) Sustainable crop-rotation pattern, and (c) Crop-rotation pattern corresponding to maximum net income return for Muzaffarnagar district.

The inclusion of fallow land in the cropping sequences is also an agricultural management practice followed by the farmers from past many centuries for restoring the soil's crop yield ability primarily by improving soil's nutrient, organic matter, and water concentrations (Nadeem et al., 2019).

4.3.3 Development of an interactive web-based dashboard for farmers

Interpreting the results by referring to the raster's presented may be challenging due to the fixed resolution of the map. Further, to identify the user's location on the map, geo-referencing has to be performed. Since this study's outcomes are a great interest to farmers, providing an accessible solution would help translate the theory into practice. The dashboard tracks the geolocation of the user and overlays the location on the map which help in the easy

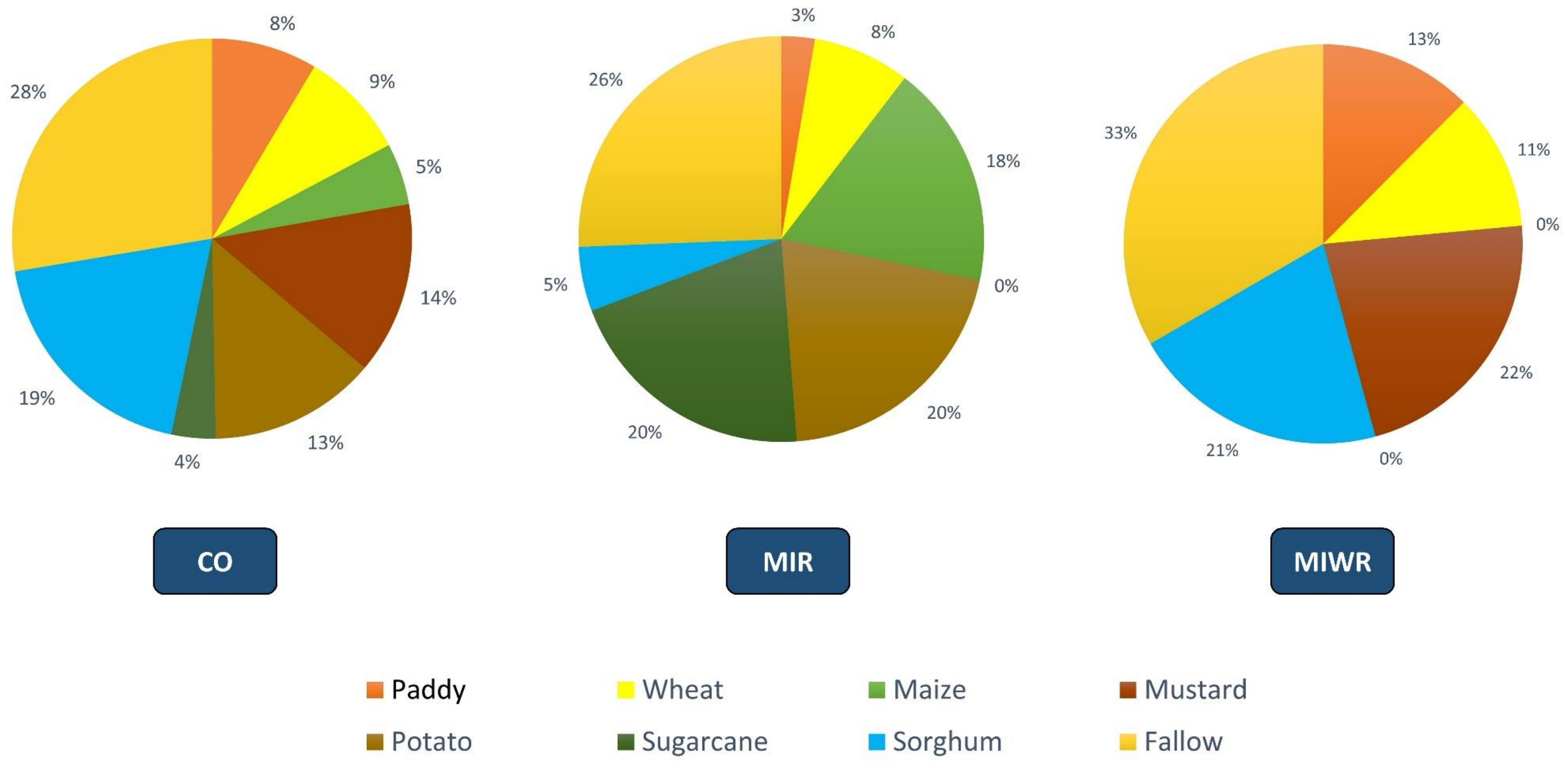


Fig. 4.7 Annual average percentage of land covered by crops under MIR, CO, and MIWR scenario.

The dashboard tracks the geolocation of the user and overlays the location on the map which help in the easy interpretation about the type of practice a farmer can adopt. The developed dashboard can be accessed at https://harishpuppala43.github.io/croprotation/ (Fig 4.8). The dashboard tracks the geolocation of the user and overlays the location on the map which help in the easy interpretation about the type of practice a farmer can adopt.

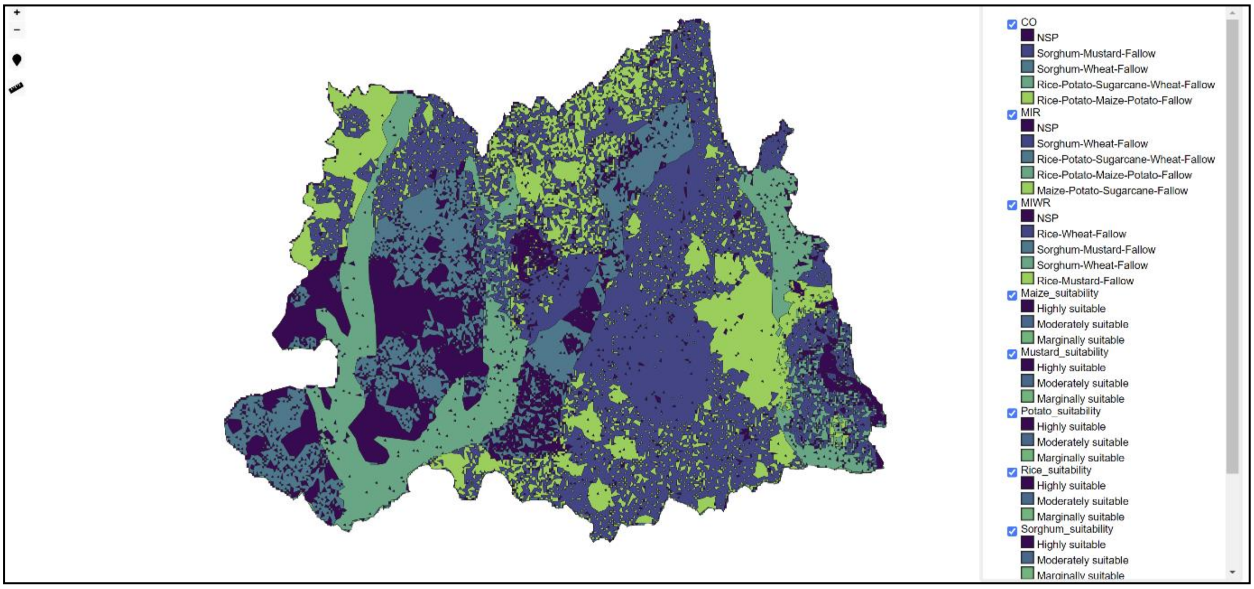


Fig. 4.8 Schematic illustration of the web-based dashboard.

Table 4.10 Net return, total water consumption, and acreage for the crop-rotation patterns under the constrained optimized scenario

Constraint optimization (CO)	**Acreage (Ha x 1000)**	**Total Water Consumption (Mm^3)**	**Net Return(Million $)**
Sorghum-Mustard-Fallow	90.48	573.06	80.46
Sorghum-Wheat-Fallow	33.26	243.89	10.67
Rice-Potato-Sugarcane-Wheat-Fallow	38.68	576.39	44.43
Rice-Potato-Maize-Potato-Fallow	53.76	521.48	53.86
NSP	44.53	0	0
Total	260.72	1914.82	189.43

Table 4.11 Net return, total water consumption, and acreage for the crop-rotation patterns under minimum irrigation water scenario

MIWR	Acreage (ha x 1000)	Total Water Consumption (Mm^3)	Net Return (Million $)
Rice-Wheat-Fallow	26.95	202.16	10.57
Sorghum-Mustard-Fallow	90.48	573.06	80.46
Sorghum-Wheat-Fallow	44.99	329.90	14.43
Rice-Mustard-Fallow	53.76	349.45	20.58
NSP	44.53	0	0
Total	260.72	1454.57	126.05

Table 4.12 Net return, total water consumption, and acreage for the crop-rotation patterns under maximum net return scenario

MIR	Acreage (ha x 1000)	Total Water Consumption (Mm^3)	Net Return (Million $)
Sorghum-Wheat-Fallow	33.26	243.89	10.67
Rice-Potato-Sugarcane-Wheat-Fallow	28.51	424.85	32.75
Rice-Potato-Maize-Potato-Fallow	0.19	1.88	0.20
Maize-Potato-Sugarcane-Fallow	154.22	2506.09	186.88
NSP	44.53	0	0
Total	260.72	3176.71	230.50

4.4 Summary

Agriculture is backbone for the subsistence of mankind either directly as food or indirectly in terms of economic commodity. It is important to efficiently utilize and maintain the agricultural regions. The agricultural land use planning in view of crop rotation practices implementation is competent to deliver greater soil fertility and high economic potential. Considering this, the study develops a framework for conserving future soil fertility, maximizing the agricultural profit, and in addition minimizing degradation of water quality and quantity by determining sustainable crop rotation patterns for the selected study area.

The proposed framework consists of integrated application of geoinformatics, stochastic pairwise comparison, and constraint optimization utilizing 7 major crops of Muzaffarnagar district in Uttar Pradesh. A hybrid system approach is used for identifying the major crops and the criteria suitable for their cultivation followed by preparation of thematic layer maps through combined use of remotely sensed geo-databases and instrumentality of Kriging tool in ArcGIS (ver. 10.9). The field observed soil chemical properties such as soil organic carbon, available nitrogen, pH, etc. for more than 2700 sample points in the study region are derived from Soil Health Card geodatabase, India. Further, the land suitability maps for 7 crops of Rabi (October to April) and Kharif seasons (May to October) namely Wheat, Sugarcane, Rice, Mustard and so on were generated by contrasting the requirements of each crop with available land potentials and classified based on Food and Agricultural Organization guidelines. The uncertainty concerning the judgment of experts has been dealt using stochastic pairwise comparison by utilizing stochastic beta pairwise comparison. The normalized difference vegetation index maps prepared using Red and Near-Infrared bands of Sentinel-2 satellite imagery for year, 2020 are used to eliminate non-vegetative land area from the predicted land cropping patterns. Finally, using the constrained optimization technique with maximization of income returns and minimization of irrigated water requirement as two objectives and various standard combinations of cropping patterns as constraints, sustainable crop rotation pattern for the district was developed. The sugarcane crop is cultivated on more than 90% of the cultivable region in the study area causing substantial lowering of ground water levels.

However, the results suggest that even disregarding the consideration of water consumption a maximum 20% of the land area can be allocated for sugarcane cultivation. Also, in addition to the principal crops, sugarcane, wheat, and rice, potato, mustard, maize, and sorghum also have good cultivation potential in Muzaffarnagar whereas only a petite amount i.e., 1.5%, 1.8%, 0.1%, and 0% of land area is used for their cultivation. With the prime focus on knowledge transfer from scientific studies to farmers, the chapter also utilized an open-source geospatial repository to develop an interactive dashboard that can fetch farmers' locations and present each crop's suitability based on optimized crop rotation practices.

Thus, the present chapter develops and offers a systematic source control technique for controlling the NPS pollution generated from agricultural fields. The chapter delivers sustainable crop rotation plans for the district of Muzaffarnagar (Uttar Pradesh, India). These plans are particularly helpful in preserving the soil fertility and controlling pest attacks as they obstruct the pest cycles through cultivation of dissimilar crops and these practices also. Thus, the use of fertilizers and pesticides is minimized at the source level/field level minimizing the ANPS pollution generation. In Section 2.2.2.1 of this thesis this source control technique has been reviewed in detail. Such integrated application of geoinformatics, stochastic pairwise comparison, and constraint optimization can provide a useful tool for agricultural land use planning unveiling the sustainable land use planning patterns which otherwise remain hidden under various personal motivations of different stakeholders. The next chapter takes a step ahead through identification of combination of conservation practices using modeling and graph networks for delivering maximum pollution reduction efficiencies while incorporating farmers' behavioural responses.

CHAPTER 5

FARMER ADOPTION-BASED RAPID NETWORKING FOR TARGETING OPTIMAL AGRO CONSERVATION PRACTICES

5.1 Introduction

Unsustainable agricultural practices are progressively being realized as the leading source of non-point source (NPS) pollution, causing the deterioration of river waters worldwide (Duda, 1993; Lam et al., 2010; Scavia et al., 2016; Wang et al., 2019). For instance, expansion of hypoxic zone in the Gulf of Mexico due to the drainage of extensive nutrients from Upper Mississippi agricultural fields (Rabalais and Turner, 2019), impairment of 22% of surface water and 28% of the groundwater in European Union (EEA, 2020), and 50% of nitrogen and phosphorus load discharged from agriculture in the longest river in China despite enforcing several laws like Water Pollution Control Law (WPCL) and Yangtze River Protection Law (YRPL) for NPS pollution control (Xie et al., 2022). The study area situated between the two most profound rivers Ganga and Yamuna situated in India, as has been discussed in the previous chapter (chapter 3), is no lesser in intensity of agriculture and fertilizer usage as compared to the countries which have their major waterbodies deteriorated indicating necessity of immediate adoption of remedial solutions (Srinivas et al., 2018).

The watershed models have been regarded as effective tools for simulating watershed scale hydrologic processes like modeling nutrients, pesticides, surface runoff, etc. (Uniyal et al., 2020). There are number of watershed-scale models available that can simulate the physical landscape processes (Verma and Jha, 2015; Kast et al., 2021). SWAT (Soil and Water Analysis Tool), an open access, semi-distributed eco-hydrological model, has been used extensively for modelling the agricultural non-point sources pollution impacts on the hydrological components in USA and other developed and developing nations across globe (Angello et al., 2021; Jaiswal et al., 2020; López-Ballesteros et al., 2023; Wang et al., 2020). SWAT is also competent for invariably handling the complex interferences of varying land uses and management practices in a computationally efficient manner (Ba et al., 2020; Purnell et al., 2020). Numerous studies conducted in the past showcase the effectiveness of SWAT in modeling the impact of a versatile range of conservation practices (like strip cropping, riparian buffers, terrace, vegetative buffers, etc.) on water quality and quantity in the agriculture-dominating landscapes (Engebretsen et al., 2019; Himanshu et al., 2019; Kaini et al., 2012; Liu et al., 2019; Uniyal et al., 2020). The BMPs are the most common, efficient, and acknowledged ways that contains agricultural NPS pollution via chemical, physical, and biological processes like filtration, adsorption, denitrification, and so on (Jain and Singh, 2019; Lam et al., 2010; Liu et al., 2019b; Sharma and Malaviya, 2021). The inconsiderate implementation of BMPs on all sites requiring pollution reduction is one of the simplest methods for targeting BMPs. But such practice would certainly be uneconomical as not all spatial units contribute substantially to river water impairments. Thus, the researchers have employed optimization algorithms for targeting the BMPs on the sites engendering maximum pollution load to meet the desired load reduction economically.

For instance, Ahmadi et al. (2013) integrated SWAT with a multi-objective genetic algorithm to determine the optimized BMP types and locations for regulating pesticides and nutrients in the Eagle Creek, Indiana. A new framework integrating Markov approach, SWAT, and NSGA-II was developed by Chen et al. (2016) for optimizing BMPs and for quantifying the water quality responses in Three Georges Reservoir Region, China. Naseri et al. (2021) presented an optimization model framework to find for cost-effective control of sediment yield and runoff in the Fariman dam watershed, Northeast of Iran by optimizing soil and water conservation practices using SWAT and Non-Dominated Sorting Genetic Algorithm-II (NSGA-II). Wu et al. (2022) used a hybrid of SWAT and entropy weight method for evaluating and screening the efficacy and cost-effectiveness of six BMP types. Despite of plethora of advanced research for developing efficient BMP delineation frameworks, majority of the proposed models lack comprehensive/integrated allocation of conservation techniques i.e., the focus is only on optimizing single BMP allocation for a spatial unit. While it has been ascertained by the past studies that every BMP has its inherent limitations (Xia et al., 2020). Thus, a mix or combination of practices is recommended as that can offset for the mutual limitations of BMPs towards attainment of the target pollution reduction goals (Jain and Singh, 2019).

The efficacious decision making on BMP selection is valuable or fruitful pivoted to their adoption in the fields. Thus, the related stakeholders including policy makers, farmers/land managers, advisors’ participation in decision making is paramount for successful planning and conservation practices optimization (EPA, 2014; Peltonen-Sainio et al., 2019). In a report, by EPA (2014), they have recognized such “human dimension” interference as complex as the natural world itself. Farmers are the decision makers and there are many factors studied by the researchers like, community culture, education, age, field size which influence their decisions and ultimately adoptions of BMPs (Peltonen-Sainio et al., 2019;

Wang et al., 2018). Instead of relying on a particular combination of these factors and indirectly identifying farmers' likelihood of BMP adoption, it would be valuable to capture the farmers' willingness directly. “Conservation identity” or CI has been realized as a profound criterion which can capture the farmers’ BMP adoption consciousness and provide a sound measure on whether the farmer will adopt BMPs in his field or not (Burnett et al., 2018; Kast et al., 2021; Zhang et al., 2016). The basic principle underlying this measure is the identity theory, i.e., the traits, convictions, and beliefs of person reflects his/her identity (McGuire et al., 2015). The conservation identity measure applied in this study queries farmers through a field questionnaire survey on the traits of a good farmer (Appendix-B, Questionnaire B 2.3) thus helps in effective in-field targeting of the BMPs.

The present chapter extends a framework facilitating the prompt field scale adoption of conservation practices by integrating robust hydrological modelling accompanied with graph network optimization and farmer’s conservation identities for attending the ever-increasing non-point source pollution in the river Ganges. The novelty of the proposed approach is its recommendation of integrated BMPs using a graph network-based optimization technique and inclusion of the farmer actors that entrenches BMPs field scale application. One of the most fertile and agriculture intensive land in India (Uttar Pradesh) discharging its agriculture wastewater in River Yamuna has been selected for demonstrating the proposed model or framework. The objectives of this chapter primarily include 1.) simulation of the discharge, nutrient and, the BMPs applicable for the study watershed using SWAT model, 2.) developing a novel integrated BMP optimization algorithm using graph theory, 3.) Incorporating farmers’ conservation identities in watershed BMP delineation.

5.2 Materials and Methods

5.2.1 Study area and proposed framework

The land area encompassing the agricultural regions of Saharanpur, Muzaffarnagar, and Meerut, the three leading agricultural districts of India’s largest food grain production state, Uttar Pradesh (IBEF, 2023) has been selected as the study area for this research. The land is situated amidst the fertile Indo-Gangetic plains and experiences a tropical climate with an annual average temperature of 23°-24° C, and precipitation of 800 to 1200 mm, is suitable for the cultivation of sugarcane, wheat, and rice crops besides maize, potato, sorghum. However, the higher relative minimum support price (MSP) and increased per capita demand for sugarcane, wheat, and rice have led to their intensive cultivation causing excessive use of fertilizers and pesticides, impairing water quality and lowering water tables, and degrading the soil fertility (DES, 2017; Kashyap and Agarwal, 2020; Kopittke et al., 2019; TD, 2017). Thus, this study proposes a framework for optimized targeting of integrated conservation practices or BMPs incorporating farmers' preferences for prompt amendment of these intimidating issues.

The proposed framework (Fig. 5.1) integrates hydrological modelling to evaluate the effect of BMP implementation on nutrient discharge at the watershed outlet. And consequently, optimizes BMP selection using a graph network optimization considering maximization of nutrient reduction and minimization of cost as objectives and targets these BMPs to the subbasins. Firstly, a hydrological model is set up based on the various watershed datasets and observed discharge and nutrient at the watershed outlet. Next, the individual BMPs were simulated in the hydrological model and their effect in terms of nitrate reduction is reported as the base scenario. Based on their reduction efficiency and costs, the optimized BMP combinations were retrieved through a graph network optimization method. Then, these BMP combinations are targeted to different subbasins in the hydrological model based on three scenarios considering farmers' conservation identities and critical nitrate pollution. Finally, the impact of optimized BMPs under three scenarios on the selected subbasins was realized. The sequence of the above-mentioned processes including complex equations is separately presented in Fig. 5.2. The major analytical segments of the proposed framework are delineated in the following sections.

5.2.2 Hydrological model setup

A recent release of ArcSWAT (2012.10.25 version) as an extension for ArcGIS 10.8 has been used to simulate the hydrological and nutrient runoff processes within the study watershed. The calibration and validation of the nitrate and river flow was executed for period 2010-2020 (both inclusive) using the monthly flow and NO_3 data obtained from the Central Water Commission, Ministry of Jal Shakti, Govt. of India, for the gauge station, Galeta, situated at the catchment outlet (Fig. 5.3). The datasets used for developing the SWAT model for the study watershed are provided in Table 5.1.

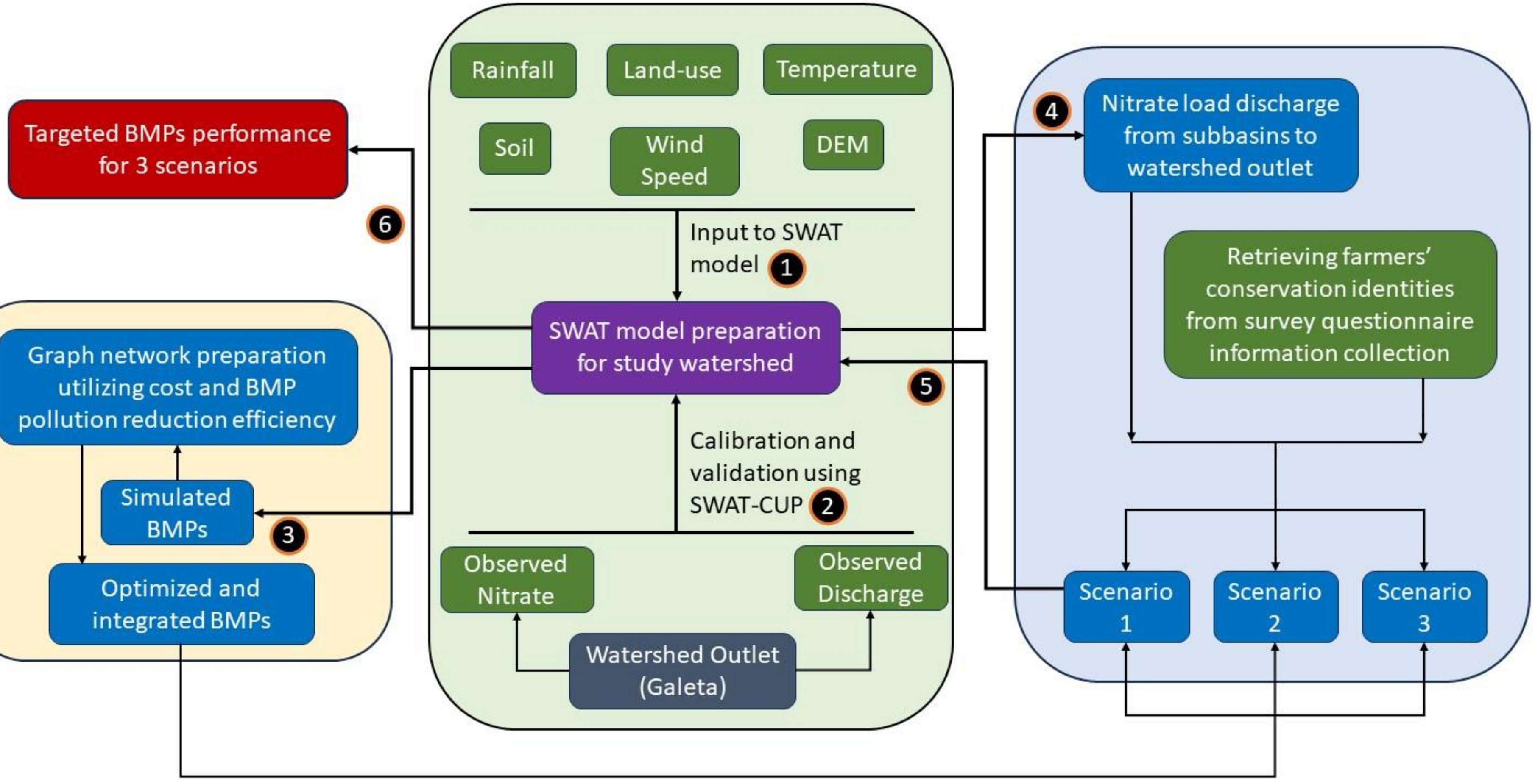
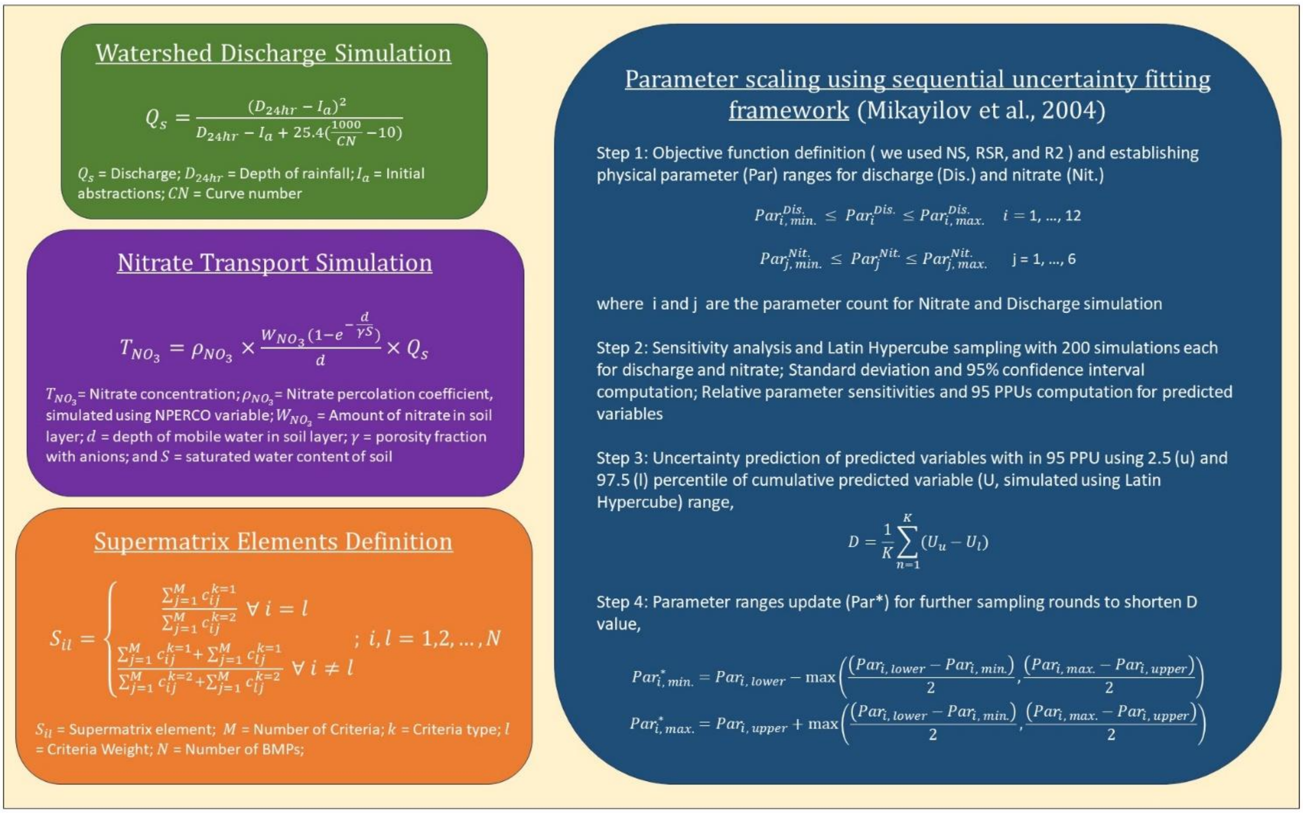


Fig. 5.1 A systematic framework for the proposed approach for prompt adoption of the conservation practices



Watershed Discharge Simulation

$$Q_s = \frac{(D_{24hr} - I_a)^2}{D_{24hr} - I_a + 25.4(\frac{1000}{CN} - 10)}$$

Q_s = Discharge; D_{24hr} = Depth of rainfall; I_a = Initial abstractions; CN = Curve number

Nitrate Transport Simulation

$$T_{NO_3} = \rho_{NO_3} \times \frac{W_{NO_3}(1 - e^{-\frac{d}{\gamma S}})}{d} \times Q_s$$

T_{NO_3} = Nitrate concentration; ρ_{NO_3} = Nitrate percolation coefficient, simulated using NPERCO variable; W_{NO_3} = Amount of nitrate in soil layer; d = depth of mobile water in soil layer; γ = porosity fraction with anions; and S = saturated water content of soil

Supermatrix Elements Definition

$$S_{il} = \begin{cases} \frac{\sum_{j=1}^{M} c_{ij}^{k=1}}{\sum_{j=1}^{M} c_{ij}^{k=2}} \ \forall\, i = l \\ \frac{\sum_{j=1}^{M} c_{ij}^{k=1} + \sum_{j=1}^{M} c_{lj}^{k=1}}{\sum_{j=1}^{M} c_{ij}^{k=2} + \sum_{j=1}^{M} c_{lj}^{k=2}} \ \forall\, i \neq l \end{cases} ;\ i, l = 1, 2, \dots, N$$

S_{il} = Supermatrix element; M = Number of Criteria; k = Criteria type; l = Criteria Weight; N = Number of BMPs;

Parameter scaling using sequential uncertainty fitting framework (Mikayilov et al., 2004)

Step 1: Objective function definition (we used NS, RSR, and R2) and establishing physical parameter (Par) ranges for discharge (Dis.) and nitrate (Nit.)

$$Par_{i,\,min.}^{Dis.} \leq Par_i^{Dis.} \leq Par_{i,\,max.}^{Dis.} \quad i = 1, \dots, 12$$

$$Par_{j,\,min.}^{Nit.} \leq Par_j^{Nit.} \leq Par_{j,\,max.}^{Nit.} \quad j = 1, \dots, 6$$

where i and j are the parameter count for Nitrate and Discharge simulation

Step 2: Sensitivity analysis and Latin Hypercube sampling with 200 simulations each for discharge and nitrate; Standard deviation and 95% confidence interval computation; Relative parameter sensitivities and 95 PPUs computation for predicted variables

Step 3: Uncertainty prediction of predicted variables with in 95 PPU using 2.5 (u) and 97.5 (l) percentile of cumulative predicted variable (U, simulated using Latin Hypercube) range,

$$D = \frac{1}{K}\sum_{n=1}^{K}(U_u - U_l)$$

Step 4: Parameter ranges update (Par*) for further sampling rounds to shorten D value,

$$Par_{i,\,min.}^{*} = Par_{i,\,lower} - \max\left(\frac{(Par_{i,\,lower} - Par_{i,\,min.})}{2}, \frac{(Par_{i,\,max.} - Par_{i,\,upper})}{2}\right)$$

$$Par_{i,\,max.}^{*} = Par_{i,\,upper} + \max\left(\frac{(Par_{i,\,lower} - Par_{i,\,min.})}{2}, \frac{(Par_{i,\,max.} - Par_{i,\,upper})}{2}\right)$$

Fig. 5.2 Compound modeling frameworks congregation involved in novel SWAT-network optimization approach.

Table 5.1 Datasets used in developing SWAT model

Category	Data	Source	Period
Weather data	Rainfall	CWC Meteorological dataset	2010-2020
	Temperature	CWC Meteorological dataset	2010-2020
	Humidity	NASA POWER	2010-2020
	Wind Speed	NASA POWER	2010-2020
Hydrological data	Runoff	CWC Guage	2013-2020
	Nitrate	CWC Gauge	2013-2020
Topographic data	Land use	ESRI 2020	2021
	Soil	FAO-UNESCO	2007
	DEM	USGS EarthExplorer	2021

The spatial datasets including the digital elevation model (DEM), land use (10 m x 10 m), soil (2 m x 2 m) have been prepared using the ArcGIS, projected, and included in the ArcSWAT model. The various subdivisions of the land use, soil, and slope along with their proportions respective to the entire are described in the Table 5.2.

Table 5.2 Areas apportioned for different land uses, soils, and slopes in the study watershed

Land use, Soil, and Slope allocation		Area (ha)	% Watershed Area
Land use	Agricultural Land – Generic (AGRL):	133757.66	85.56
	Sugarcane (SUGC)	69139.33	44.22
	Winter Wheat (WWHT)	49945.11	31.94
	Rice (RICE)	14673.22	9.39
	Forest-deciduous (FRSD)	5402.59	3.46
	Perennial Indiangrass (INDN)	48.58	0.03
	Residential (URBN)	17017.95	10.89
	Water (WATR)	103.43	0.07
Soil	FAO Soil Classification:		
	Jc45-2a-3739	28707.75	18.36
	Lo5-2a-3810	127622.46	81.64
Slope	0 – 0.75	65866.86	42.13
	0.75 – 1.5	63709.76	40.75
	1.5 – 2.25	20013.46	12.8
	> 2.25	6740.11	4.31

Eventually, the study watershed was apportioned into 31 subbasins and/or 146 hydrological response units (HRUs). Further, the evaluation of the developed model was carried out using the SUFI-2 algorithm available in the SWAT-CUP application (Abbaspour et al., 2007). The simulated river flow and the nitrate loads were calibrated and validated using the monthly time steps for the period 2013-2017 and 2018-2020 in the SWAT CUP using 12 and 18 parameters (Table 5.3) sensitive to flow and nitrate loads.

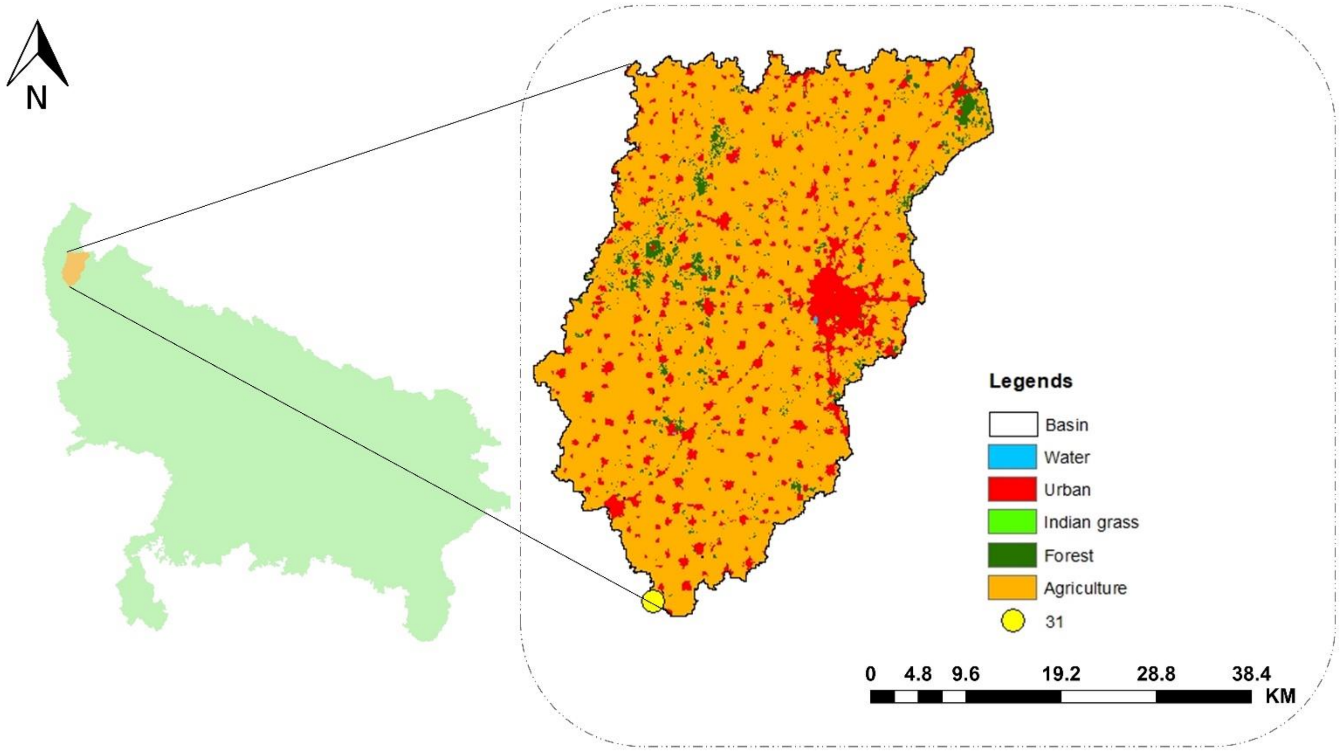


Fig. 5.3 Study area location in the Uttar Pradesh (India) and its's various land use classes.

Table 5.3 Calibration parameters range and fitted values for discharge and nitrate.

Sr. No.	***Parameters**	**Calibration range**	**Calibrated values (Discharge)**	**Calibrated Values (Nitrate)**
1	r__CN2.mgt	-20% to 20%	.017	-0.181
2	v__ALPHA_BF.gw	0 to 1	0.2125	0.7375
3	a__GW_DELAY.gw	0 to 500	493.75	26.25
4	a__GWQMN.gw	-1000 to 1000	-605	-215
5	r__ESCO.hru	0 to 100%	0.7375	0.0325
6	v__REVAPMN.gw	0 to 1000	22.5	932.5
7	v__GW_REVAP.gw	0.02 to 0.2	0.1465	0.02135
8	r__SOL_AWC().sol	-20% to 20%	.063	-0.197
9	v__EPCO.hru	0 to 1	0.4625	0.6575
10	v__CH_N2.rte	0.01 to 0.3	0.034	0.044075
11	v__CH_K2.rte	100 to 500	173	377
12	v__RCHRG_DP.gw	0 to 1	0.2075	0.0025

Sr. No.	***Parameters**	**Calibration range**	**Calibrated values (Discharge)**	**Calibrated Values (Nitrate)**
13	v__RCN.bsn	1 to 5	---	1.33
14	v__N_UPDIS.bsn	5 to 30	---	27.3125
15	v__SHALLST_N.gw	0 to 1000	---	47.5
16	v__ERORGN.hru	1 to 4	---	1.0375
17	v__NPERCO.bsn	0 to 1	---	0.5125
18	v__LAT_ORGN.gw	0 to 100	---	18.75

**The initials (r,v,a) before parameters abbreviations decides the auto-calibration parameter ranges; where r=relative change to initial value, v=replacement of value within given range, a=addition from given range to initial value. While parameter extension, i.e., .sol or .gw, shows the processes handled by parameters; mgt=crop cover management, gw=groundwater, sol=soil water dynamics, bsn=entire watershed scale, rte=water routing, hru=water dynamics at HRU level. Parameters explained: ALPHA_BF=Base-flow alpha factor (days); CH_K2 = Effective hydraulic conductivity in main channel alluvium; CH_N2 =Manning's "n" value for the main channel; CN2=SCS runoff curve number; EPCO=Plant uptake compensation factor; ERORGN=Organic N enrichment ratio for loading with sediment; ESCO=Soil evaporation compensation factor; GW_DELAY=Groundwater delay (days); GWQMN=Threshold depth of water required for return flow to occur in the shallow aquifer (mm); GW_REVAP=Groundwater "revap" coefficient; LAT_ORGN=Organic N in the base flow (mg/L); N_UPDIS=Nitrogen uptake distribution parameter; NPERCO=Nitrate percolation parameter; RCHRG_DP=Deep aquifer percolation fraction; RCN=Concentration of N in rainfall (mg N/L); REVAPMN=Threshold depth of water in the shallow aquifer for "revap" to occur (mm); SHALLST_N=Initial concentration of nitrate in shallow aquifer (mg N/L or ppm); SOL_AWC=Available water capacity of the soil layer.*

Various statistical parameters including the percentage of observed data enveloped by the modelling result (the 95PPU) - P-factor, thickness of the 95PPU envelope - R-factor, coefficient of determination - R^2 (Eq. 5.1), Nash-Sutcliffe - NS (Eq. 5.2), and ratio of the root mean square error to the standard deviation of the measured data – RSR (Eq. 5.3) have been used to evaluate the model performance.

$$NS = 1 - \frac{\sum_i (X_o - X_s)_i^2}{\sum_i (X_{o,i} - X_o)^2} \tag{5.1}$$

$$R^2 = \frac{\left\{\sum_i (X_{o,i} - \overline{X_o})(X_{s,i} - \overline{X_s})\right\}^2}{\sum_i (X_{o,i} - \overline{X_o})^2 \sum_i (X_{s,i} - \overline{X_s})^2} \tag{5.2}$$

$$RSR = \frac{\sqrt{\sum_i (X_o - X_s)_i^2}}{\sqrt{\sum_i (X_o - X_s)^2}} \tag{5.3}$$

Where, X is the variable (i.e., discharge or nitrate), the subscripts o and s refer to observed and simulated variable, and i is the ith data in the complete dataset range. The model results for the calibration and validation periods of the simulated river flow and nitrate load are presented in Table 5.4. The detailed definitions of these statistical measures could be found in (Jhs et al., 2019; Abbaspour, 2015).

Table 5.4 Uncertainty prediction and model performance evaluation for steam discharge and nitrate

Parameter	Monthly stream flow		Nitrate load	
	Calibration	Validation	Calibration	Validation
P-factor	0.77	0.6	0.88	0.89
R-factor	14.29	2.12	1.35	2.44
R^2	0.64	0.73	0.76	0.75
NS	0.6	0.62	0.76	0.68
RSR	0.63	0.62	0.49	0.56

5.2.3 Conservation practices simulation for nitrate load management

A total of four conservation practices viz., riparian buffers, conservation tillage, cover crops, and nutrient management were simulated through sensitive parameter identification and their adjustments (Zhang et al., 2023) in the SWAT CUP to replicate their field scale performance reported by the past research (Agriculture, 2012; Nouri et al., 2022; Udias et al., 2016). A survey (Appendix-B, Questionnaire B 2.3) conducted among the farmers in the study region revealed that practices such as riparian buffers and cover crops are seldom practiced. The riparian buffers are effective in absorbing the pollutants present in the agricultural runoff. They serve as filters and are effective when situated along the edge of waterbodies draining agricultural runoff (Luo et al., 2017). Conservation tillage reduces soil disturbance and thereby minimizes erosion and improves organic matter concentration, etc. by limiting the plowing process carried out in the conventional agricultural systems (Lv et al., 2023; Xia et al., 2020). The nutrient management is pivoted at the careful and considerate application of the fertilizers in the right quantity, right time and, right location for attaining optimal growth of the plants. This curtails the overdose of fertilizers and eventually minimizes the nutrient runoff (Tomer, 2014). The cover crops are different from the cash crops which are cultivated for sale and harvesting (Merfield, 2019). These are primarily used for covering the soil which helps in improving soil fertility, controlling soil erosion, organic matter, infiltration, and soil structure and so on.

5.2.4 Optimal BMP selection using modified analytic network process

The identification of optimal BMP combination that results in maximum efficiency, i.e., maximization of the ratio of nitrate load reduction to the cost is materialized by modifying the traditional analytical network process, first introduced by Saaty (1996). The modified ANP offers a high degree of flexibility in choosing any possible combination of BMPs, i.e., selection of any individual BMP or an integrated set of BMPs based on cost and nitrate reduction criteria, consolidated under two general criteria, i.e., profit (e.g., nitrate reduction) and penalty (like the cost of BMP). The general categories allow incorporation of further criteria such as phosphate reduction, and perceived environmental benefits.

We formulated the modified ANP technique considering a general case with N BMPs as possible alternatives (nodes) denoted by a_i $(i = 1,2, \dots, N)$. Each a_i has its corresponding criteria $c = \{c_{i1}^k, c_{i2}^k, \dots, c_{ij}^k\}$ where j denotes the number of criteria and k indicates whether the criteria category i.e., benefit $(k = 1)$ or cost $(k = 2)$. Thus, the ANP supermatrix $S_{il}; (i = 1,2, \dots N);$ $(l = 1, 2, \dots N)$ elements were defined using efficiencies of cost and nitrate reduction of rendered by each BMP (Fig. 5.2, Supermatrix elements definition). Then the supermatrix $S = (S_{il})$ is developed as shown below

$$S = \begin{bmatrix} S_{11} & \cdots & S_{1N} \\ \vdots & \ddots & \vdots \\ S_{N1} & \cdots & S_{NN} \end{bmatrix} \tag{5.4}$$

Further, we normalized the matrix S using a normalization scheme,

$$\hat{S} = S \;\phi\; SJ \tag{5.5}$$

where ϕ is elementwise division and J is an all-ones matrix.

In order to calculate final ANP efficiencies (i.e., efficiencies for the complete BMP network; which are different from individual or integrated BMP efficiencies) using inter-dependencies $(S_{il};\ i \neq l)$ and feedback $(S_{il};\ i = l)$ (Fig. 5.4) we stabilized $\hat{S}$ as follows,

$$S^* = \lim_{\lambda \to \infty} \hat{S}^{2\lambda+1} \tag{5.6}$$

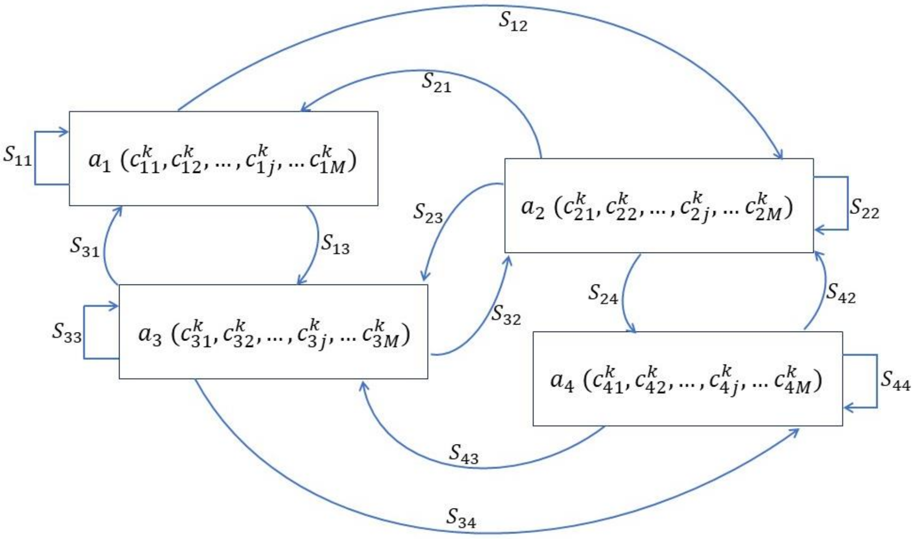


Fig. 5.4. The loop for alternatives or BMPs indicates the inter-dependencies among the elements of the alternatives. The arc, for example, from alternative a$_1$ to a$_2$, indicates the outer dependence among the elements in a$_1$ on the elements in a$_2$.

When the limit in Eq. (5.6) is convergent and exclusive, we obtain the matrix S^*. Finally, to select the best combination of BMPs with two, three, or more integrated BMPs (based on the user's choice) from all the available BMP set of N is trivial from $S^* = (S_1^*, S_2^*, \dots, S_N^*)$ and achieved by employing the operation

$$\underset{i}{\operatorname{argsort}} S^* = \left|\left\{S_j \mid S_j < S_i\ ; \forall\, S_i, S_j \in S^*\right\}\right| \tag{5.7}$$

This operation is so designed to further fabricate the next best combinations of the selected BMPs by repeating the operation (Eq. 5.7). Further a python code for the developed network is provided in Appendix-A.

5.3 Results

5.3.1 Evaluation and inclusion of farmers' conservation identities in SWAT model

The SWAT model developed for the study area has been calibrated and validated using the observed monthly discharge and nitrate from the Galeta site located on Hindon River basin (a tributary of Yamuna River). The years 2010-2012 has been used as the warm period for stabilizing and balancing the hydrological stocks in the SWAT model (Ayana and Srinivasan, 2019). While the observed data from years 2013-2017 and 2018-2020 was utilized for calibration and validating the flow respectively. The Figs. 5.5 and 5.6 presents the calibration and validation of simulated monthly discharge and nitrate based on the observed dataset periods. The performance of the developed model based on the various statistical metrics is summarized in the Table 5.4 and presented through the Figs. 5.7 and 5.8 using R^2 scatter plots highlighting the satisfactory performance and representation of the hydrological system for the considered study area. Except for some high and low peaks of flow which could be partly true because most of the hydrological model finds their limitation in simulating the extreme events or multiple storms in a day (Himanshu et al., 2019).

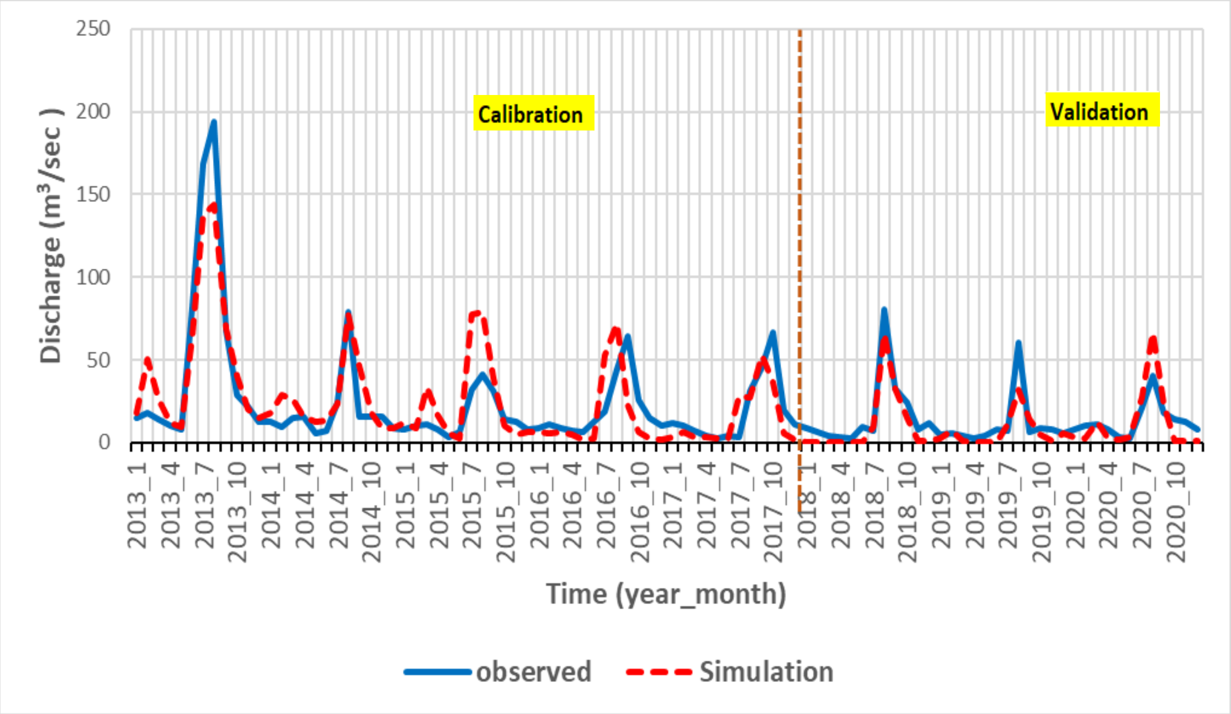


Fig. 5.5 Calibration and Validation of simulated discharge at the watershed outlet.

Further, the responses collected from the 20 farmers encompassing four subdistricts have been used for establishing the conservation identities of the farmers in the study area. The CI of the farmers' (Fig. 5.9) for subbasin has been assigned based on their closest proximity to an individual sub-district using the buffer tool in the ArcGIS. The 12 subbasins influenced by the Shahpur subdistrict were found to have the resilient CI (90%) and the subbasins (10 in number) influenced by the Purkaji subdistrict have minimal CI (10%). While the subbasins corresponding to Morna and Khatauli exhibited weak (61.54%) and moderate (67.69%) CI respectively.

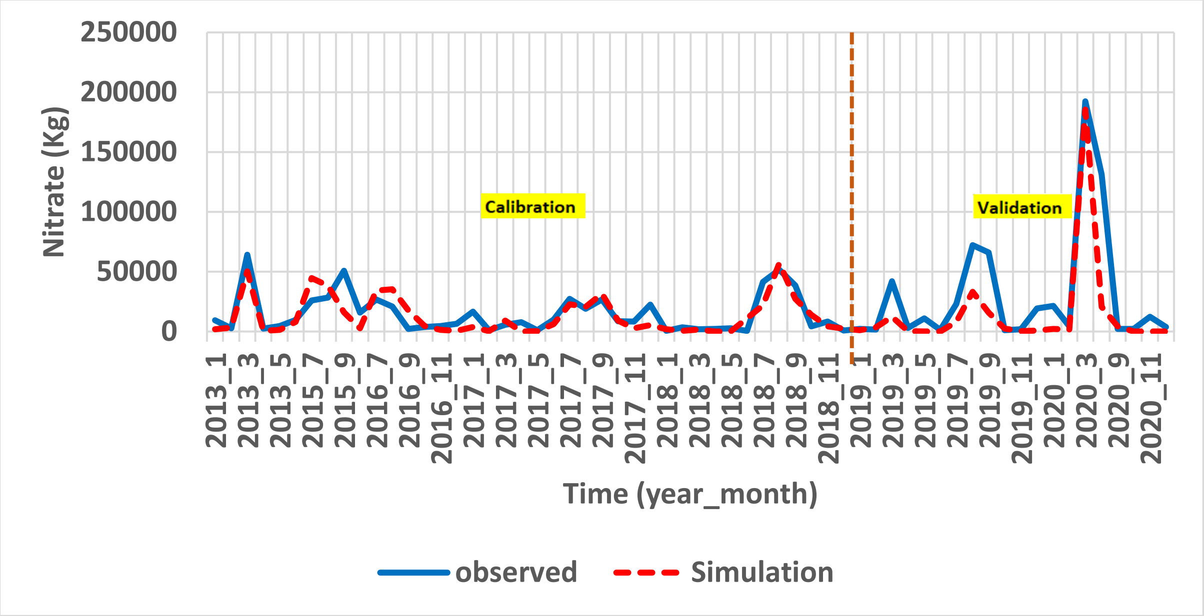


Fig. 5.6 Calibration and Validation of simulated nitrate at the watershed outlet.

5.3.2 Assigning BMPs to the subbasins incorporating graph theory optimization approach

The nitrate load in the subbasin reaches computed using developed model showed substantial variations across the watershed subbasins (Fig. 5.10). The 50%, 75%, 100% subbasins influenced by Purkaji, Khatauli, and Shahpur showed low (< 2.5 kg/acre) to weak (2.5 to 5 kg/acre) contribution of nitrate loads whereas all the subbasins related to Morna fall under high to severe (>5 kg/acre) nitrate load production class. The subbasins undergoing moderate and severe production of nitrate loads have been considered for suggesting the BMPs under the critical nutrient loss regions scenario. The adoption of the BMPs under farmers' conservation identity scenario considers only subbasins having moderate and resilient farmer CI. In this study, the SWAT model has been utilized to assess or evaluate the five prominent BMPs applicable in the study watershed viz. riparian buffers, conservation tillage, cover crops, nutrient management, and grade stabilization structures for checking the nutrient load generation in the subbasin reaches. The implementation of the cover crop on all the subbasins showed maximum reduction (84%) in nitrate loads while at the same time-consuming maximum costs (105 $/acre).

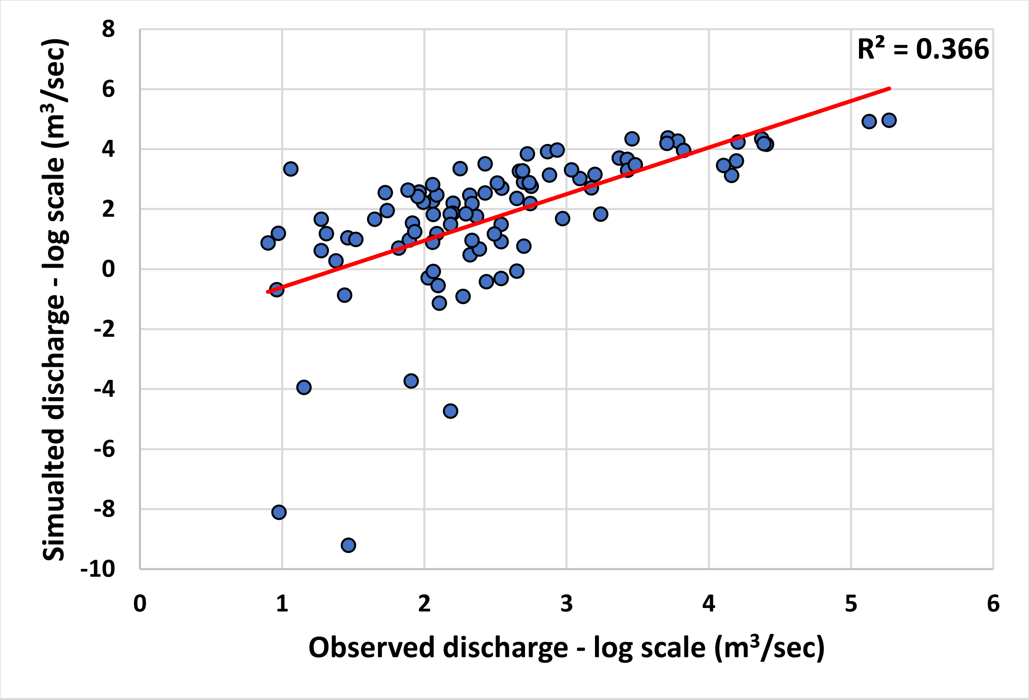


Fig. 5.7 Coefficient of determination scatter plot for the simulated discharge.

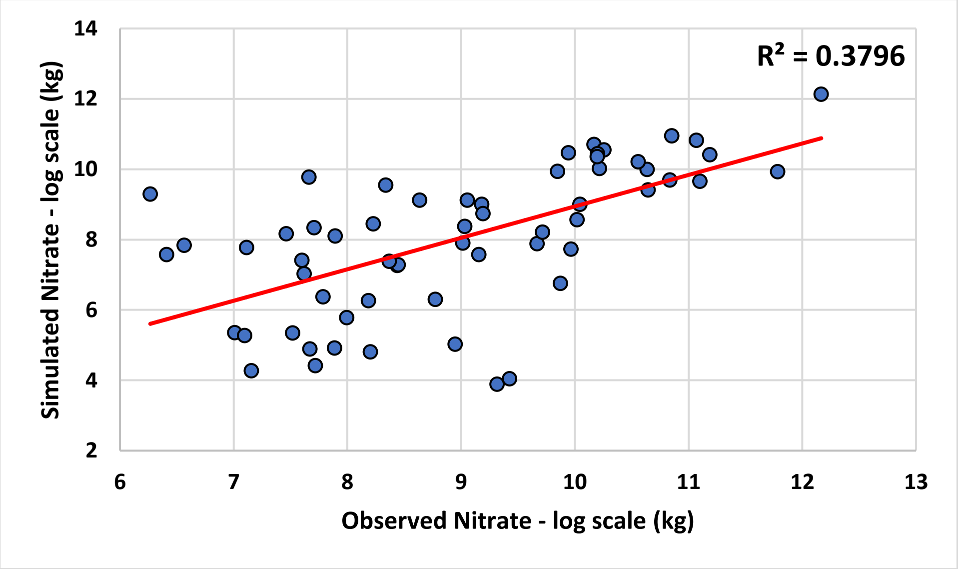


Fig. 5.8 Coefficient of determination scatter plot for the simulated nitrate.

While on the other hand, the nutrient management practice though offers a low application rate (11.6 $/acre) but reduces only 13% of nitrate load. The expenditure or cost incurred in implementing different BMPs along with their various nutrient reduction potentials have been provided in Table 5.5.

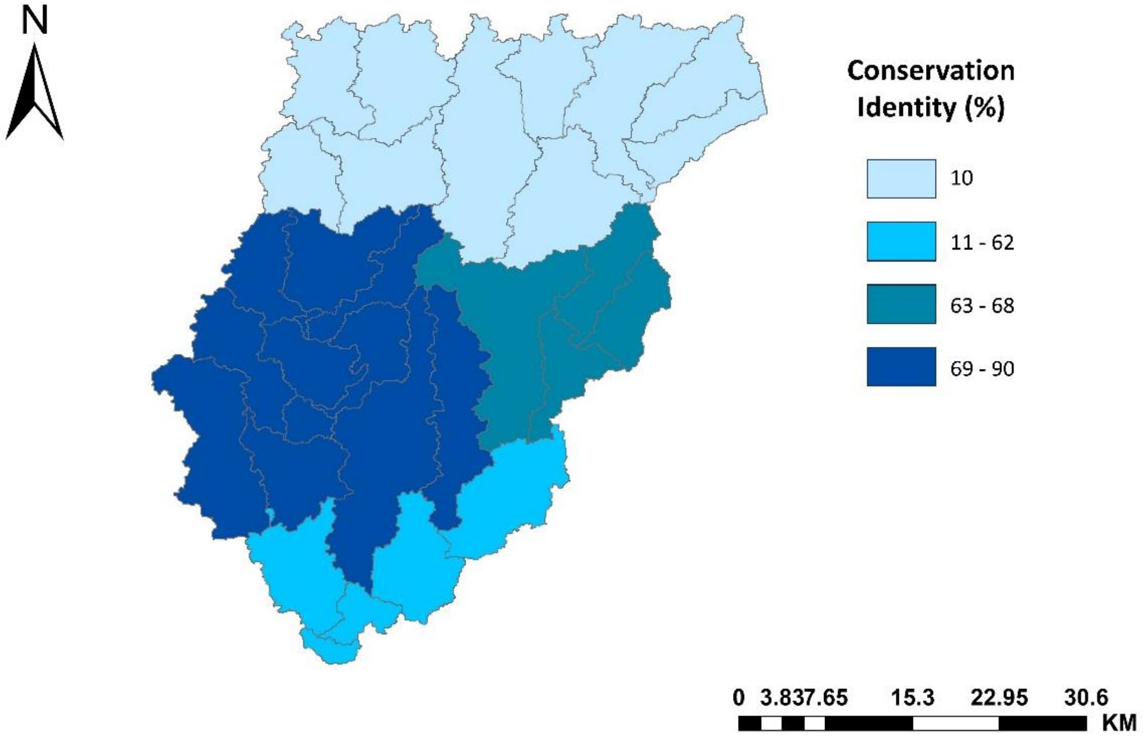


Fig. 5.9 Farmers’ conservation identities bifurcation for the study watershed

Table 5.5 Cost and nitrate reduction potential of BMPs

Best management practices	Cost ($/acre)	Nitrate load reduction (%)
Nutrient Management	11.6	13
Conservation Tillage	10	68
Cover Crops	105.1	84
Riparian Buffer	23.4	80

Different combinations of these four BMPs ranging from the collective application of all 4 BMPs to a single BMP have been considered to identify the most efficient combination using modified analytic network process algorithm as discussed in the section 5.2.4. The consideration of two criteria, i.e., cost and reduction potential for each BMP resulted that the combination of riparian buffers and conservation tillage is most efficient (0.1882) followed by the nutrient management and conservation tillage (0.1592) and then nutrient management and riparian buffers (0.1128).

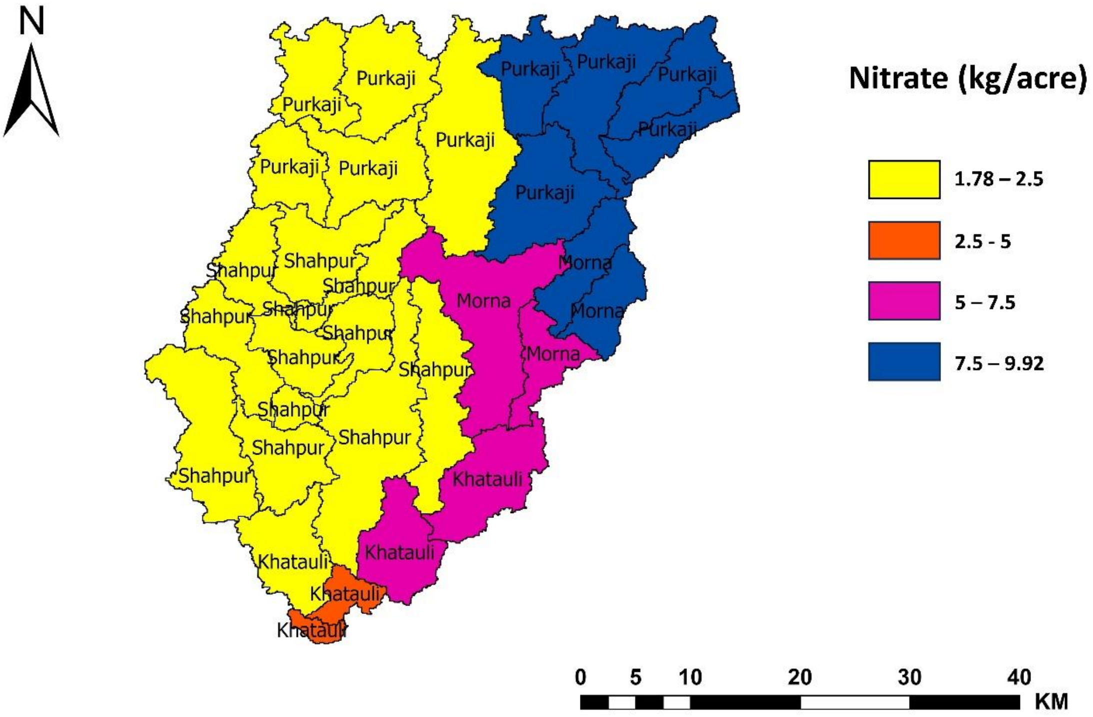


Fig. 5.10 Nitrate load intensity in the different subbasin reaches and their source sub-districts

5.3.3 Targeting BMP adoption to subbasins based on nitrate load generation and farmer's CI

The BMP adoption to all subbasins and its effects in terms of cost, nitrate reduction, and efficiency which is essentially a tradeoff between cost and nutrient reduction potential have been deliberated in the previous section. The discussion in the present section is pivoted at utilizing the combination of optimal practices engendered in the previous section for gauging the impact of three different scenarios (Table 5.6). First scenario i.e., targeting based on critical subbasins, constrained the BMP adoption to the 11 subbasins (Fig. 5.11a) involving subbasins corresponding to the Purkaji, Morna and Khatauli subdistricts delivering maximum efficiency of 0.279 under riparian buffer and conservation tillage BMPs.

Whereas combination of conservation tillage and nutrient management BMPs under the first scenario yielded an efficiency of 0.236. The efficiencies, cost, nitrate reduction for the selected BMPs under four different scenarios have been summarized in Table 5.7.

Table 5.6 Scenarios to evaluate the optimal BMP combinations performance under various subbasins selections

Scenario	Subbasins selection and definition	Number of Subbasins	Subdistricts
Base	All Subbasins	31	Purkaji, Morna, Khatauli, Shahpur
First	Subbasins with critical or Severe Nitrate load production	11	Purkaji, Morna, Khatauli
Second	Subbasins with moderate and resilient farmer conservation identity	15	Morna, Shahpur
Third	Subbasins with moderate and resilient farmer conservation identity and critical Nitrate load production	4	Morna

Table 5.7a Model analysis results for the optimized set of BMPs under three scenarios

BMP combination ↓	Nitrate Reduction (Gg)				Costs (million $)			
Scenario ⟶	Base *(Real)*	1st	2nd	3rd	Base *(Real)*	1st	2nd	3rd
Riparian Buffer + Conservation Tillage	12.2 *(6.8)*	6.05	2.5	1.55	70.2 *(44.1)*	21.7	20.8	5.59
Conservation Tillage + Nutrient Management	6.66 *(3.71)*	3.31	1.38	0.84	45.4 *(28.5)*	14	13.4	3.58
Riparian Buffer + Nutrient Management	7.65 *(4.26)*	3.8	1.58	0.97	73.6 *(46.2)*	22.7	21.8	5.86

Table 5.7b Model analysis results for the optimized set of BMPs under three scenarios

BMP combination ↓	Efficiencies			
Scenario ⟶	Base *(Real)*	1st	2nd	3rd
Riparian Buffer + Conservation Tillage	0.19 *(0.15)*	0.28	0.12	0.28
Conservation Tillage + Nutrient Management	0.16 *(0.13)*	0.24	0.10	0.23
Riparian Buffer + Nutrient Management	0.11 *(0.09)*	0.17	0.07	0.17

In the 2nd scenario, a different set of subbasins for BMP adoption were nominated (Fig. 5.11b) based on the farmers' CI criteria alone and resulted in efficiencies lower than the first scenario for all 3 BMP combinations. While scenario 3 showed (Fig. 5.11c) a significant increment of efficiencies in comparison to the 2nd scenario which considers both farmer CIs as well as the critical nitrate subbasins.

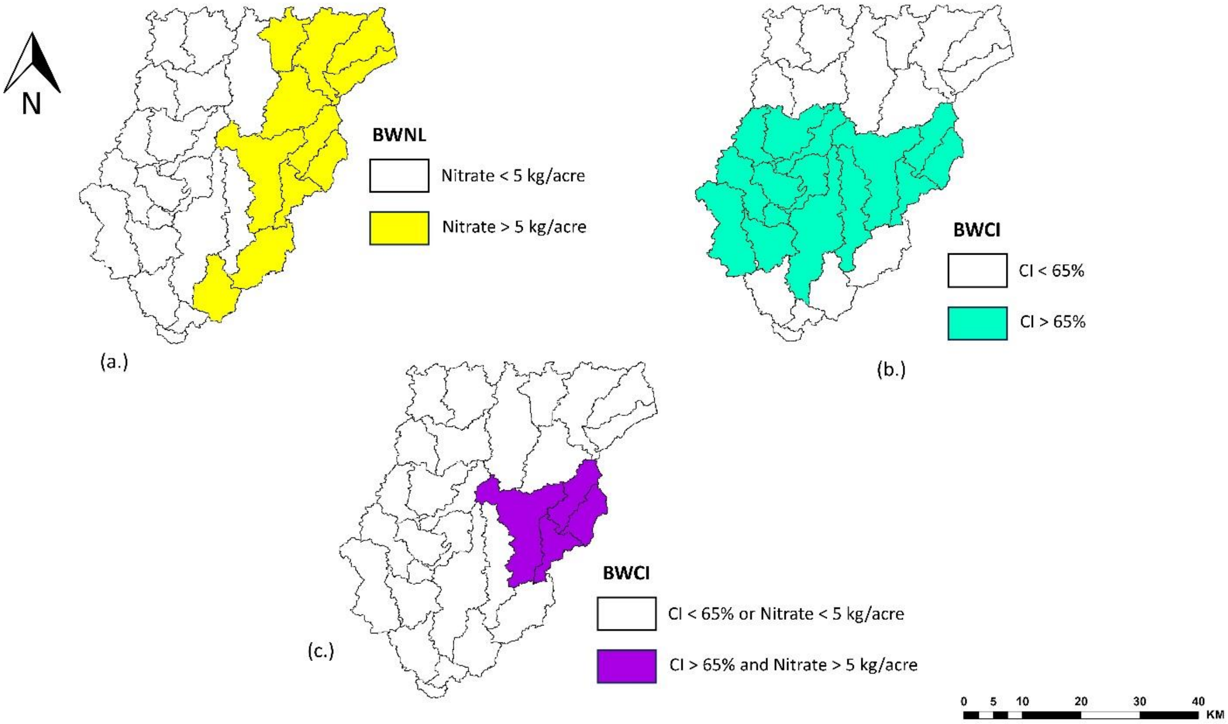


Fig. 5.11 Watershed subbasins selection corresponding to a.) critical nitrate load, b.) high farmer conservation identities and, c.) their combination scenarios.

5.4 Discussion

5.4.1 Efficacy of the developed hydrological model for targeting BMPs

The performance of the developed SWAT model was evaluated using two sets of parameters, i.e., uncertainty in the model prediction and the evaluation of the model performance. The general measure of the good uncertainty modeling suggests that high p-factor (towards 1) and low r-factor value (towards zero) (Mengistu et al., 2019). Also, Abbaspour (2015) suggests that the p-factor of more than 0.7 and the r-factor near around 1 for the calibration and validation of flow from a watershed are acceptable. Thus, the p-factor of 0.77 and 0.88 for calibration of the discharge and nitrate showed that about 77% and 88% of the observed flow and observed nitrate has been explained by the simulated model and the R-factor (2.12 and 2.44) obtained corresponding to the validation of flow and nitrate is also within the acceptable ranges where its low value highlights the lower model uncertainty or low 95PPU thickness.

Besides these, the performance evaluation parameters for the calibration and validation processes, i.e., ($0.76 > R2$ & $NS > 0.6$, $-4 < PBIAS < 52.4$, $RSR < 0.63$) also delivered satisfactory results indicating a decent explanation of the observed variables by the simulated modelling results. Moreover, the underestimation and overestimation peaks in the simulated results could be explained based on the unavailability or lack of the observed dataset at the study location (Poméon et al., 2018), unaccountability of the anthropogenic influences on land-surface-air nexus by the model, or inaccuracy/errors in the metrological, land use, soil information datasets (Bennour et al., 2022). Further, the use of empirical SCS curve number for runoff simulation in SWAT could also answer the perceived inaccuracy as SCS curve number forsakes the length and intensity of the storm.

5.4.2 Farmer conservation identities, critical nitrate, and graph theory

The resilient or high conservation identity of the farmers in the subbasins corresponding to the Shahpur sub-district could be true because of the interplay of multiple factors. Like according to the survey conducted (Appendix-B, Questionnaire B 2.3) among the farmers of 4 sub-districts in the study region, the average age of the farmers in Shahpur is least (around 32) compared to other sub-districts and their education level is university graduate and post-graduate. The age factor features receptivity while the education level features comprehensibility (Damianos and Giannakopoulos, 2002). The young and educated farmers are considerably more adaptive to the new technologies and more prepared to take risks also because they have/can afford extended planning horizons; the researchers in past have also pointed to young farmers as “gamblers” which justifies relatively higher environmentally stewardship among the farmers in Shahpur subdistrict compared to others (Damianos and Giannakopoulos, 2002; EC, 2023; Tina Casey, 2018). Similarly, the farmers’ CIs in other sub-districts could be explained. On the other hand, the high nitrate pollution in the selected subbasins within the watershed could be explained based on their trend, i.e., the higher concentration of the nitrate load is noticed in the subbasins situated alongside the river channel. This could be true due to the fact that the regions situated near the river channels/waterbodies have always been found more agriculture intensive and major sight of industrial/commercial activities as they have easy access to water as well as drainage (Khan et al., 2021).

Further, the graph theory optimization approach suggested three different options for controlling the nitrate pollution. These options include the combined use of riparian buffers and conservation tillage, conservation tillage and nutrient management, and nutrient management and riparian buffers. The highest efficiency of riparian buffers and conservation tillage combination could be explained based on their physical characteristics. The conservation tillage is a source control practice that minimizes the pollution generation at its onset preventing the dispersal of pollution into the atmosphere. The conservation tillage minimizes rainfall and tillage effects by the way of protecting soil surface using crop residues (Awad et al., 2012; Meier et al., 2017). The application of riparian buffers (an end treatment technique) would be helpful in controlling whatever amount of pollution is left over post conservation tillage treatment.

Recognizing the high efficiency of the riparian buffers featured by retention, absorption, and denitrification as has also been reported by the researchers in the past (Luo et al., 2017; Mander, 2008), the combination of two these two techniques as most efficient could be justified. The higher efficiency of the conservation tillage and nutrient management in comparison to nutrient management and riparian buffers could be true because of the minimal cost requirements of the nutrient management. The conservation tillage as mentioned by the previous researchers (Clausen et al., 1996; Nouri et al., 2022; Xia et al., 2020) has high pollution reduction capacity. Though the nutrient management is not that potent at nitrate pollution prevention (only 10-15% reduction) (Udias et al., 2016) but its little support at minimal cost leverages the source control potential of the conservation tillage surpassing the combined efficiency of the riparian buffers and nutrient management (Singh et al., 2021; Yadav et al., 2019). The combination if riparian buffer with nutrient management is weaker in comparison to riparian buffer and conservation tillage owing to nutrient management being weaker source control practice than conservation tillage.

5.4.3 Importance of farmer conservation consciousness in effective BMP targeting

In the present section, the results obtained by constraining the BMPs adoption to the selected subbasin based on the three different scenarios are discussed. The efficiencies in the first scenario (only subbasins with critical loading), as expected, are substantially elevated by 47% to 50% than the apparent (not real) base scenario (Table 5.7), i.e., considering only subbasins with critical nitrate concentration a 50% (12.2 Gg for RB+CT) of nitrate reduction in base scenario can be achieved at 30% (21.7 million $ for RB+CT) of the total cost demanded in the base scenario. However, the scenario 1 follows an inherent assumption that the BMPs in all subbasins functions homogenously or have equivalent or consistent performance throughout the watershed. The participation of farmers is an essential prerequisite for the successful implementation, execution, and performance of BMPs (Ma et al., 2012) which is an outcome of multitude of factors such as farmers' education level, age, financial status, farm size, community factors like influence of neighbours, connection with the environmentally oriented professionals at local, district, or state level (Adam Reimer, 2012). The consideration of the involvement of the farmers' factors also imposed significant changes (lowered) to the nitrate reduction, costs, and efficiencies of the base scenario pointed as 'Real' results in the base scenario (Table 5.7).

Consequently, the assumption of homogeneity in farmer participation throughout the watershed or adoption of BMPs solely based on critically polluted subbasins is ineffectual. Therefore, the 2nd scenario includes farmers' conservation identity for the selection of subbasins for BMP adoption. Though, the inclusion of CIs ensures or takes into account the subjectivity of BMPs performance/acceptance in the subbasins, the efficiencies of the BMPs were considerably lowered (Table 5.7), even more than the base scenario. Which simply highlights the fact that the subbasins with critical nitrate concentrations are incongruous with the subbasins having moderate or resilient CIs. To counteract the limitations of first two scenarios 3rd scenario was created which is an intersection of the first and second scenario delivering high BMP performance/efficiency comparable to the case when only critical subbasins were selected. However, there are only few subbasins (4 subbasins influenced by Morna sub-district) with high farmer CI and critical nitrate pollution. This suggests or guides the governmental policies and watershed planners that instead of extending homogenous educational programs, incentivization policies and learning opportunities for the farmers, these should be more focussed towards the farmers inhabiting subbasins with critical nutrient pollution concentrations.

5.5 Summary

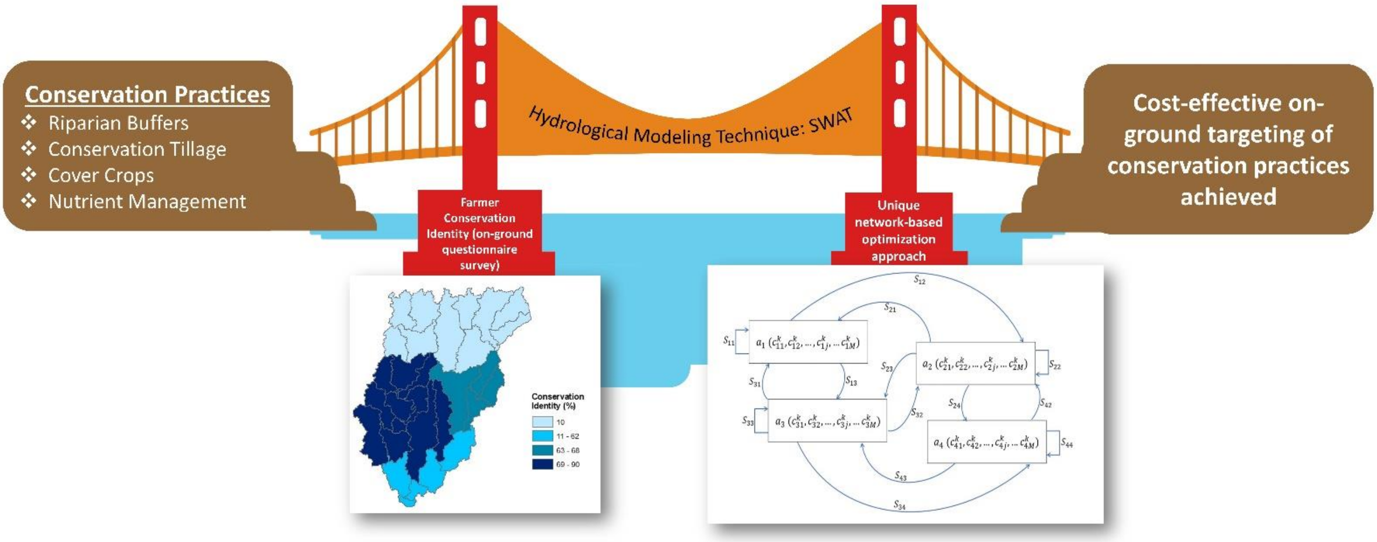


Fig. 5.12 Summary of the propsed SWAT-network based BMP delineation.

The ever-increasing pollution in the river waters worldwide needs immediate addressal before the situations turns irreversible. The non-point source from the agricultural fields is gradually being identified as the prominent source of river water pollution. The present study proposes an effective approach for the immediate amelioration of the agricultural non-point source pollution by integrating a novel graph network-based optimization technique and farmers' conservation identity measure with systematic watershed hydrological modelling using Soil and Water Assessment Tool (SWAT) (Fig. 5.12). The conservation practices or BMPs including riparian buffer, conservation tillage, cover crops, and nutrient management applicable to the agriculture intensive land area combining the portions of Saharanpur, Muzaffarnagar (majority), and Meerut and draining in to the Hindon River (a tributary of Yamuna) has been selected for demonstrating the proposed model. A field-scale survey for the four major subdistrict of the study watershed was conducted for deciphering the conservation identity, age, and education of the local farmers through one-to-one interactions. After successful calibration and validation of the SWAT model using monthly discharge and nitrate for the study watershed for the years 2010-2020, the selected BMPs were simulated using SWAT CUP. Next, the optimized BMP combination through graph network optimization and farmer conservation identities were incorporated in the developed hydrological model supplying the effective strategies for BMP selection and targeting. The study results suggested that the adoption of riparian buffer and conservation tillage for the subbasins corresponding to the

Morna subdistrict in the study area is most efficient (0.28) (ratio of nitrate reduction (kg) to the total BMP cost ($)) for nitrate reduction.

The present chapter offers an immediate ANPS pollution remedial strategy through incorporation of farmer environmental consciousness and response together with graph network-based optimization allowing adoption of integrated source, process, and as well as the end control practices. The chapter also underlined the importance of inclusion of farmer behavioural response for effective dissemination of BMP implementation plans excluding which the BMP performance studies could be greatly biased and misleading. The following chapter works on fortifying the on-ground implementation of the precision agricultural practices, which in fact is a support to all other conservation practices, through identification of challenges inhibiting their on-ground acceptance.

CHAPTER 6

PRECISION AGRICULTURAL PRACTICES IMPLEMENTATION FORTIFICATION USING FUZZY FAULT TREE ANALYSIS

6.1 Introduction

Conservation practices are deemed reliable techniques for handling the agricultural non-point source pollution. The precision agriculture practices, pivoted at optimizing the application of chemical fertilizers and pesticides in fields and thus controlling the pollution generation at source, could serve to enhance the performance or reduce the load on all other conservation practices. Also, the incorporation of precision agriculture practices along with other viable methods can enhance the cost-effectiveness, i.e., saving costs by limiting the use of fertilizers etc. and also by lowering the load/reducing requirements of other practices. Thus, recognizing the importance of implementation of the precision agriculture practices, the present chapter systematically identifies or pinpoints the factors that check the adoption of one other essential source control technique, i.e., precision agriculture in the study region, Muzaffarnagar (Uttar Pradesh, India). Precision agriculture began in the mid-1980s with the use of new technologies to improve fertilizer applications by varying rates and blends according to the needs of the field (Sajith et al., 2022). Currently, the concept has been applied to a variety of practices, crops, and countries. Precision agriculture has the potential to meet the rising food demands across the globe while augmenting farmers' income. The advancement in artificial intelligence, internet of things, remote sensing, sensor technologies, farm machinery, and optimized agro-economic models have made precision agriculture a reality by transforming the traditional farming approaches and, thus, paving the way for various start-ups and established food and agro-industries to develop technologies for the digitization of data-driven agriculture (Rallapalli et al., 2022).

For example, Wireless sensor networks and agricultural robots are prominently used to collect data related to soil conditions (temperature, quality, and moisture), crop health, and weather patterns and then transmit that data wirelessly to a central hub or computer. This allows farmers to monitor their crops and fields in real-time and to make adjustments to irrigation, fertilization, and other aspects of their farming operations based on the data they collect (Thilagavathi, 2013; Ojha et al., 2015). This information can be used to optimize crop yields and reduce the use of resources such as water and fertilizer (Thakur et al., 2019). In addition, wireless sensor networks and agricultural robots can also be used to monitor air quality and climate conditions, allowing farmers to reduce time and labour costs and make more informed decisions about when and how to plant and harvest their crops (Yi et al., 2015; Nair et al., 2021; Bechar, 2021).

Despite its promising results, there has been a significant variation in the adoption of precision agriculture techniques (PATs) across cropping systems, regions, and countries, but it is being progressively introduced and evaluated around the world (Jastrzębska et al., 2022). There is rarely an immediate adoption of new technologies in agriculture. Despite many efforts being placed into persuading farmers to adopt precision agriculture technologies, this process is complex and is affected by a variety of factors (Kendall et al., 2022). In many places, due to their remote location, farmlands lack access to cooperative societies that provide help with seeds, fertilizers, and tilling machines. The inaccessibility of the facilities results in a lack of resources and a further delay in implementing modern agricultural methods (Soma et al., 2019). In India, the majority of farmers are already struggling due to unsecured loans from local lenders who charge them exorbitant interest rates. This element has been a significant obstacle for some farmers, as they are unable to earn the necessary funds to apply new technologies (ET Bureau, 2018). The public and private sectors' efforts to increase the adoption of precision agriculture techniques have not yielded the intended results in terms of awareness and adoption, despite its success in increasing productivity, decreasing costs, and generating higher returns (Katke, 2019).

Uncertainties associated with precision agriculture models are typically the result of randomness and imprecision. The random character of input variables, such as cost, energy consumption, use of fertilizers and chemicals, location of farmlands, level of awareness etc. causes uncertainty due to randomness. The uncertainty resulting from imprecision arises due to the farmers’ opinions such as the perceived utility of precision agriculture practices, risk aversion to adopting new technologies and indecisiveness towards acceptance of precision agriculture techniques. (Srinivas and Singh, 2018; Shubham et al., 2022). Additionally, due to variations in geography, farmer experience, wealth, education level, and other factors, the process of risk assessment for the adoption of precision agriculture becomes challenging. Therefore, a robust approach is needed to bridge the gap between precision agriculture technology and it’s on ground implementation by scientifically assessing the associated challenges. Such an approach would give clarity to the practitioners on how to how to best utilize the precision agriculture technologies in an economically sound and technically viable manner. Fault tree analysis (FTA), a quantitative approach for calculating the failure probabilities of a system's components, is one of the most effective risk analysis techniques, which can be used for assessing the challenges associated with precision agriculture adoption. FTA is a top-down, deductive failure analysis that uses Boolean logic to estimate the system's reliability. In FTA, the definition of a top event is followed by its resolution into intermediate and fundamental events that are interconnected by logic gates. Using the rules of Boolean algebra, the fault tree is analysed as a set of Boolean equations. (Cheliyan and Bhattacharyya, 2018; Kuzu et al., 2019).

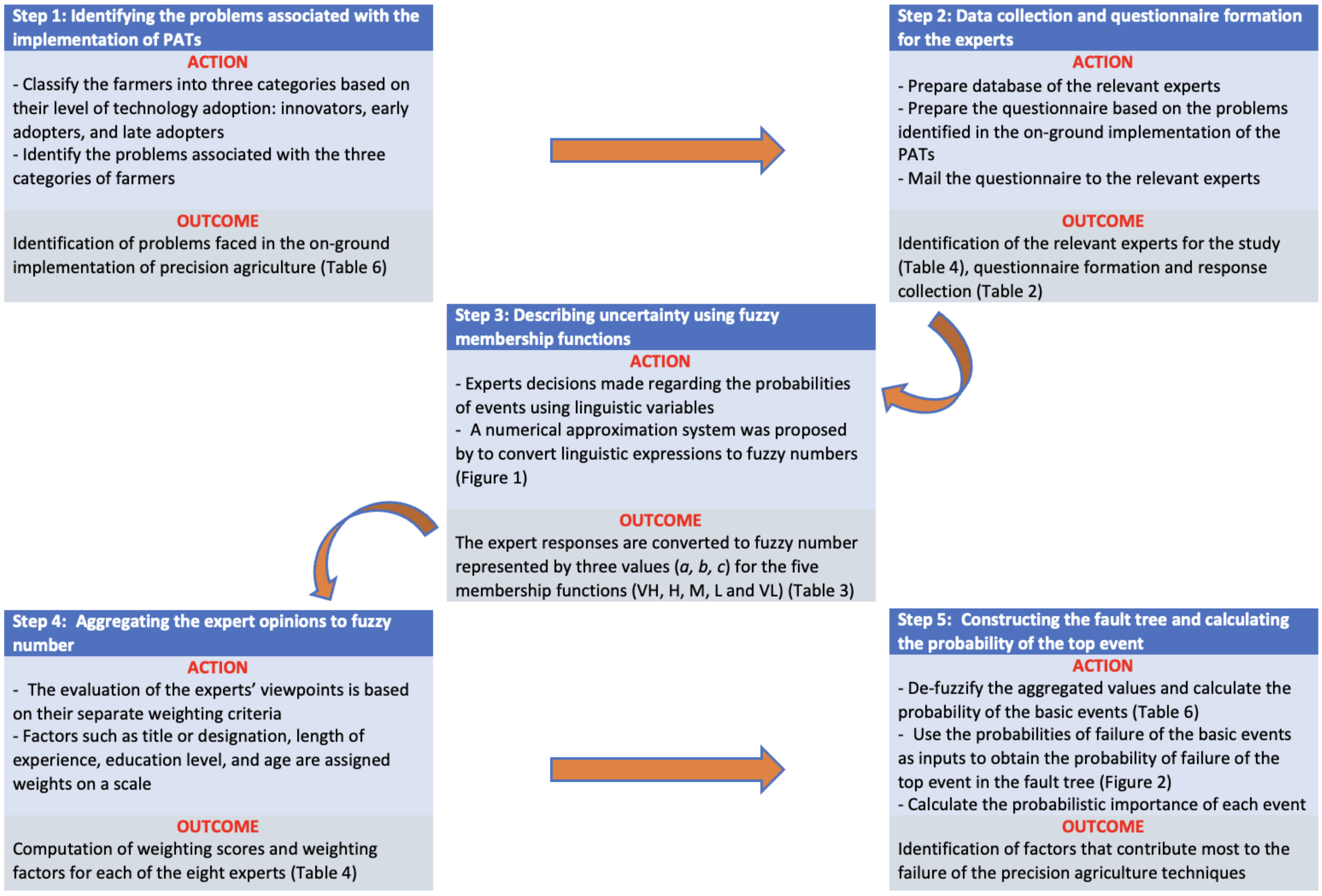
The failure probabilities of the fundamental/basic events (BE) are exact values in conventional FTA. Due to a lack of data, however, it is impractical to precisely estimate the failure probabilities of BEs (Yazdi et al., 2019). When there is a lack of precise data, it is often necessary to operate with approximations or probabilities. The fuzzy logic-based approach provides a method for determining failure probability values when few quantitative data are available, where the BE probabilities are considered fuzzy integers. In this chapter, fuzzy fault tree analysis has been employed to assess the challenges associated with the adoption of PATs for ensuring its on-ground implementation in Muzaffarnagar district in Uttar Pradesh (India). In particular, the study aims to (a) assess and compare the opinions of the various stakeholders associated with precision agriculture, (b) identify the challenges faced by farmers towards implementing PATs, and (c) use Fuzzy Fault Tree Analysis (FFTA) to incorporate uncertainties associated with precision agriculture experts for ensuring on-ground implementation of PATs. The results of this study could serve as a basis for developing a comprehensive guide to increasing the on-ground implementation and adoption of the PATs by the farmers.

6.2 Methodology

To construct the fault tree, the study broadly categorized the farmers into three groups based on their level of technology adoption: innovators, early adopters, and late adopters. Prior research has discovered a strong correlation between the level of technology adoption and the kinds of consumers (Rogers, 1962; O’Shea et al., 2018). Innovators are among the first to adopt new technology. They take chances, have a high level of acceptance, and engage closely with other innovators. They typically have financial stability, allowing them to absorb technological failures' repercussions. Farmers who fall under the group of early adopters use technology after varying amounts of time. The adoption period for early adopters is substantially longer than that of innovators. Farmers who fall into the group of late adopters have shown little to no interest in modern farming technologies. They have an aversion to change and believe that new technologies will be a waste of money and time that will not benefit them. These farmers adhered more closely to conventional farming practices and have little financial liquidity (Soma et al., 2019). The determinants of precision farming for each category of farmers were categorised as a resource related, technological, social or behavioural and environmental. These determinants are considered as the variable for the research study as well. Muzaffarnagar district, as presented in the Fig. 4.1 in chapter 4, is also considered as a study area for the present research. Fig. 6.1 depicts the schematic procedure adopted in this chapter. Thus, this chapter aims to provide farmers with cost-effective precision agriculture-based solutions for preserving soil fertility, maximizing agricultural profit, minimizing agricultural pollution and water usage.

6.2.1 Describing uncertainty using fuzzy membership functions

In this chapter, interviews with a total of eight experts were conducted. Based on their working experience, knowledge, and expertise, the stakeholders (experts) made decisions by offering their opinions regarding the probabilities of events. Since specialists cannot precisely assess the probabilities of events, they typically use linguistic idioms such as ‘very low (VL)’, ‘low (L)’, ‘moderate (M)’, ‘high (H)’, and ‘very high (VH)’ to convey their likelihood. The linguistic expressions used by the decision makers were converted to fuzzy numbers by utilising a numerical approximation system (Rai et al., 2022). Each triangular fuzzy number is represented by three values (a, b, c) for the five membership functions (VH, H, M, L and VL) shown in Fig. 6.2 and is summarized in Table A2. A total of 21 basic events (BEs) (Table 6.1) have been identified which represent the challenges associated with on-ground implementation of precision agricultural technologies in the study area. Experts have given their opinion on these BEs. The comprehensive questionnaire used for conducting interviews and procuring experts’ opinion is presented in Appendix-B, Questionnaire 2.1. The expert opinions are summarized (Table A3) and converted to fuzzy values (Table 6.2). The basic events can be categorized into different categories based on their nature and the factors that contribute to them. Environmental BEs refer to events related to the natural environment and may be caused by natural disasters, climate change, or pollution. Resource-related BEs refer to events related to the availability or allocation of resources, such as financial, physical, or human resources. Behavioural/social BEs refer to events related to



Step 1: Identifying the problems associated with the implementation of PATs

ACTION

- Classify the farmers into three categories based on their level of technology adoption: innovators, early adopters, and late adopters
- Identify the problems associated with the three categories of farmers

OUTCOME

Identification of problems faced in the on-ground implementation of precision agriculture (Table 6)

Step 2: Data collection and questionnaire formation for the experts

ACTION

- Prepare database of the relevant experts
- Prepare the questionnaire based on the problems identified in the on-ground implementation of the PATs
- Mail the questionnaire to the relevant experts

OUTCOME

Identification of the relevant experts for the study (Table 4), questionnaire formation and response collection (Table 2)

Step 3: Describing uncertainty using fuzzy membership functions

ACTION

- Experts decisions made regarding the probabilities of events using linguistic variables
- A numerical approximation system was proposed by to convert linguistic expressions to fuzzy numbers (Figure 1)

OUTCOME

The expert responses are converted to fuzzy number represented by three values (*a, b, c*) for the five membership functions (VH, H, M, L and VL) (Table 3)

Step 4: Aggregating the expert opinions to fuzzy number

ACTION

- The evaluation of the experts' viewpoints is based on their separate weighting criteria
- Factors such as title or designation, length of experience, education level, and age are assigned weights on a scale

OUTCOME

Computation of weighting scores and weighting factors for each of the eight experts (Table 4)

Step 5: Constructing the fault tree and calculating the probability of the top event

ACTION

- De-fuzzify the aggregated values and calculate the probability of the basic events (Table 6)
- Use the probabilities of failure of the basic events as inputs to obtain the probability of failure of the top event in the fault tree (Figure 2)
- Calculate the probabilistic importance of each event

OUTCOME

Identification of factors that contribute most to the failure of the precision agriculture techniques

Fig. 6.1 Schematic procedure adopted in the chapter

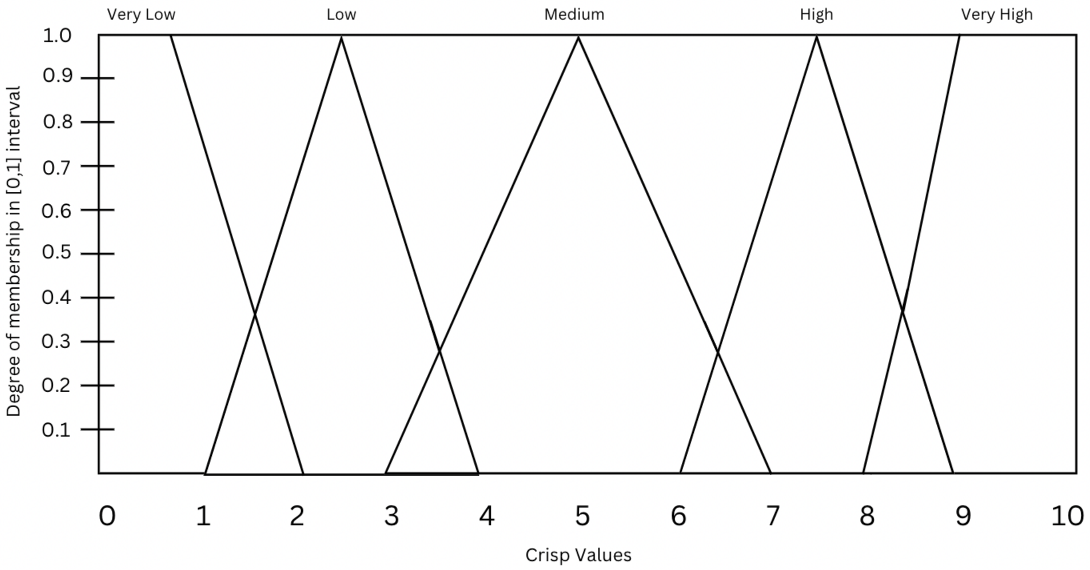


Fig. 6.2 Membership functions of the linguistic variables

human behaviour and social interactions, such as conflicts, misunderstandings, or cultural differences. Technological BEs refer to events related to technology use, such as software failures, cyber-attacks, or equipment malfunctions. Understanding and categorizing basic events is an important part of risk management because it helps organizations identify and prioritize potential risks and develop strategies to mitigate or prevent these risks from occurring.

Table 6.1 Basic events used for assessing the challenges in adopting precision agriculture techniques in the study area

Basic Event (BE)	Description
BE1	Cost of technology implementation
BE2	Dependability on pesticides and chemicals
BE3	Not accessibility to sustainability practices in agriculture
BE4	Disposal of e-waste (piles of discarded IoT tools and computers)
BE5	Operation of the smart sensors and other gadgets can lead to heavy energy consumption
BE6	Loss of manual employment (replacement for on-farm manual labour)
BE7	Limitation of technology use
BE8	Risk of malware and data thefts is a risk
BE9	Incompatibility between different equipment and hardware device
BE10	Lack of financial support
BE11	Not applicable or difficult/costly for small land holdings
BE12	Scarcity of resources such as power supply and internet access
BE13	Lack of installation/ training assistance

Basic Event (BE)	Description
BE14	Lack of regulatory and institutional policies that promote both a national and international agenda for PA adoption
BE15	Lack of awareness of different technologies
BE16	Lack of knowledge of controlling viruses and pests
BE17	Low ROI on technology due to duration
BE18	Rigidity to adopt new technology
BE19	Overdependency on traditional methods of farming
BE20	Over reliance on weather conditions
BE21	Alternative technologies made adoption less attractive

Table 6.2 Expert opinions converted to fuzzy values for 21 basic events

Basic Event	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8
BE1	(6,7.5,9)	(3,5,7)	(6,7.5,9)	(8,9,9)	(6,7.5,9)	(8,9,9)	(8,9,9)	(6,7.5,9)
BE2	(6,7.5,9)	(8,9,9)	(3,5,7)	(6,7.5,9)	(8,9,9)	(8,9,9)	(3,5,7)	(6,7.5,9)
BE3	(3,5,7)	(1,2.5,4)	(3,5,7)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)	(3,5,7)	(6,7.5,9)
BE4	(3,5,7)	(6,7.5,9)	(3,5,7)	(6,7.5,9)	(3,5,7)	(6,7.5,9)	(3,5,7)	(6,7.5,9)
BE5	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)	(3,5,7)	(3,5,7)	(3,5,7)	(1,2.5,4)	(3,5,7)
BE6	(6,7.5,9)	(3,5,7)	(3,5,7)	(6,7.5,9)	(3,5,7)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)
BE7	(3,5,7)	(3,5,7)	(3,5,7)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)	(3,5,7)	(3,5,7)
BE8	(3,5,7)	(3,5,7)	(6,7.5,9)	(3,5,7)	(3,5,7)	(1,2.5,4)	(6,7.5,9)	(6,7.5,9)
BE9	(1,2.5,4)	(6,7.5,9)	(6,7.5,9)	(3,5,7)	(6,7.5,9)	(3,5,7)	(6,7.5,9)	(6,7.5,9)
BE10	(3,5,7)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)	(3,5,7)	(6,7.5,9)	(6,7.5,9)
BE11	(3,5,7)	(8,9,9)	(6,7.5,9)	(6,7.5,9)	(8,9,9)	(8,9,9)	(6,7.5,9)	(8,9,9)
BE12	(1,1,2)	(8,9,9)	(3,5,7)	(8,9,9)	(6,7.5,9)	(8,9,9)	(3,5,7)	(6,7.5,9)
BE13	(3,5,7)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)
BE14	(6,7.5,9)	(8,9,9)	(3,5,7)	(8,9,9)	(6,7.5,9)	(8,9,9)	(3,5,7)	(6,7.5,9)
BE15	(1,2.5,4)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)	(3,5,7)	(6,7.5,9)	(6,7.5,9)
BE16	(1,2.5,4)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)	(3,5,7)	(6,7.5,9)	(6,7.5,9)
BE17	(3,5,7)	(6,7.5,9)	(3,5,7)	(8,9,9)	(3,5,7)	(8,9,9)	(8,9,9)	(6,7.5,9)
BE18	(8,9,9)	(8,9,9)	(6,7.5,9)	(8,9,9)	(6,7.5,9)	(8,9,9)	(6,7.5,9)	(6,7.5,9)
BE19	(3,5,7)	(8,9,9)	(3,5,7)	(6,7.5,9)	(6,7.5,9)	(8,9,9)	(3,5,7)	(8,9,9)
BE20	(8,9,9)	(8,9,9)	(3,5,7)	(6,7.5,9)	(6,7.5,9)	(3,5,7)	(3,5,7)	(8,9,9)
BE21	(6,7.5,9)	(8,9,9)	(3,5,7)	(8,9,9)	(3,5,7)	(6,7.5,9)	(6,7.5,9)	(6,7.5,9)

For example, BE2, BE3, BE4 and BE5 are categorized as environmental BEs in Table 6.3 since they are related to the natural environment.

6.2.2 Aggregating the expert opinions

Table A4 represents the experts selected for the study based on their expertise and knowledge regarding precision agriculture techniques and their implementation; experts from various disciplines are enlisted to evaluate the failure probability of the BEs in the form of language terms. This was accomplished by creating an appropriate questionnaire. The experts' viewpoints are evaluated based on their separate weighting criteria, as their opinions and levels of knowledge vary. As illustrated in Table A5, factors such as (a) title or designation, (b) length of experience, (c) education level, and (d) age are assigned weights on a scale from 1 to 5. The expert's weighting score is the sum of these weights for attributes. Then, the weighting factor for each expert is calculated by (Cheliyan and Bhattacharyya, 2018) using equation (6.1):

$$Weighing\ factor\ of\ the\ expert = \frac{Weighing\ score\ of\ the\ expert}{Sum\ of\ weighing\ scores\ for\ all\ experts} \quad (6.1)$$

Table A4 gives the weighting scores and factors computed for each of the eight experts in our study.

6.2.3 De-fuzzifying the aggregated values and calculating the probability of the basic events

The experts provide each Basic Event (BE) a rating (Table 6.2). All ratings for a specific BE must be pooled or aggregated to obtain a single opinion. The linear opinion pool (Clemen, 1999; Yazdi et al., 2020) has been used to calculate the aggregate using equation (6.2).

$$M_i = \sum_{j=1}^{N} A_{ij} w_j \ \ (i = 1,2,3 \ldots N) \quad (6.2)$$

where N is the number of *BEs*, j is the number of experts, w_j is the weighting factor of the expert j, A_{ij} is the linguistic expression (either a, b, or c) of the i^{th} BE given by the expert j according to Table A3, and M_i is the aggregated (resultant) triangular fuzzy number of the *BE* X_i. The values of M_i for each '*BE'* are displayed in the fifth column of Table 6.3. The defuzzification of all *BE*s leads to their Fuzzy Probability Score (FPS) values which have been obtained by the gravity centre method. For a triangular membership function (*a, b, c*), the *FPS* can be obtained in the form of equation (5.3) (Rai et al., 2022):

$$x = \frac{a+4b+c}{6} \quad (6.3)$$

The *FPS* of all *BE*s (X_i) were then converted to their fuzzy failure probability, $P(X_i)$, given in the eighth column of Table 6.3. The fuzzy failure probability (Wei et al., 2020), is given by equations (6.4-6.5):

$$P(x) = \begin{cases} \frac{1}{10^k} \; for\ FPS \neq 0 \\ 0 \;\; for\ FPS = 0 \end{cases} \tag{6.4}$$

$$k = 2.301 \left(\frac{1-FPS}{FPS}\right)^{1/3} \tag{6.5}$$

Table 6.3 Aggregated fuzzy values of the basic events

BE	Description	Category of Farmer	Category of Event	Aggregated fuzzy numbers (M)	FPS	K	P(Xi)
BE1	Cost of technology implementation	Innovators	Resource Related	(0.641,0.769,0.859)	0.7562	1.5839	0.0261
BE2	Dependability on pesticides and chemicals	Innovators	Environmental	(0.568,0.709,0.817)	0.6981	1.7449	0.0180
BE3	Not accessibility to sustainability practices in agriculture	Innovators	Environmental	(0.431,0.596,0.761)	0.5963	2.0232	0.0095
BE4	Disposal of e-waste (piles of discarded IoT tools and computers)	Innovators	Environmental	(0.418,0.59,0.761)	0.5895	2.0420	0.0091
BE5	Operation of the smart sensors and other gadgets can lead to heavy energy consumption	Innovators	Environmental	(0.369,0.539,0.709)	0.5393	2.1846	0.0065
BE6	Loss of manual employment (replacement for on-farm manual labour)	Innovators	Behavioural/Social	(0.48,0.641,0.803)	0.6413	1.8997	0.0126
BE7	Limitation of technology use	Innovators	Technological	(0.411,0.584,0.757)	0.5843	2.0566	0.0088
BE8	Risk of malware and data thefts is a risk	Innovators	Technological	(0.37,0.538,0.706)	0.5378	2.1889	0.0065
BE9	Incompatibility between different equipment and hardware device	Innovators	Technological	(0.427,0.585,0.743)	0.5850	2.0545	0.0088
BE10	Lack of financial support	Early Adopters	Resource Related	(0.493,0.653,0.812)	0.6525	1.8690	0.0135

BE	Description	Category of Farmer	Category of Event	Aggregated fuzzy numbers (M)	FPS	K	P(Xi)
BE11	Not applicable or difficult/costly for small land holdings	Early Adopters	Resource Related	(0.623,0.754,0.841)	0.7393	1.6314	0.0234
BE12	Scarcity of resources such as power supply and internet access	Early Adopters	Resource Related	(0.494,0.614,0.716)	0.6083	1.9900	0.0102
BE13	Lack of installation/ training assistance	Early Adopters	Technological	(0.536,0.688,0.841)	0.6885	1.7711	0.0169
BE14	Lack of regulatory and institutional policies that promote both a national and international agenda for PA adoption	Early Adopters	Behavioural/Social	(0.566,0.708,0.817)	0.6971	1.7478	0.0179
BE15	Lack of awareness of different technologies	Early Adopters	Behavioural/Social	(0.464,0.617,0.769)	0.6165	1.9673	0.0108
BE16	Lack of knowledge of controlling viruses and pests	Early Adopters	Behavioural/Social	(0.464,0.617,0.769)	0.6165	1.9673	0.0108
BE17	Low ROI on technology due to duration	Early Adopters	Technological	(0.53,0.677,0.785)	0.6639	1.8381	0.0145
BE18	Rigidity to adopt new technology	Late Adopters	Behavioural/Social	(0.673,0.795,0.869)	0.7791	1.5180	0.0303
BE19	Overdependency on traditional methods of farming	Late Adopters	Behavioural/Social	(0.518,0.668,0.788)	0.6583	1.8534	0.0140
BE20	Over reliance on weather conditions	Late Adopters	Behavioural/Social	(0.518,0.668,0.788)	0.6583	1.8534	0.0140
BE21	Alternative technologies made adoption less attractive	Late Adopters	Technological	(0.532,0.682,0.814)	0.6758	1.8058	0.0156

6.2.4 Constructing the fault tree and calculating the probability of the top event

A typical fault tree is composed of AND and OR gates. The 'AND' gate denotes that the output event will occur if all input events occur, whereas the 'OR' gate denotes that the output event will occur if any input event occurs. The fault tree designed for the given problem (Fig. 6.3) consists of OR gates only since the failure simultaneously depends on multiple categories of farmers. For better clarity, Fig. 6.4 separately shows the top event (TE) and Innovators’ logic gate with events and their probabilities of failure (i.e., the failure of precision agriculture implementation is denoted by T to the basic events (BEs) X_1 through X_N, where N is the total number of Bes. Similarly, Fig. 6.5 represents the early and late adopters' logic gate with events and their probabilities of failure. The likelihood of the event X_i failing is $P(X_i)$. The probability of failure of the top event, represented by P(T) for scenarios in which the connecting gate is either AND or OR, is then calculated using equation (6.6):

$$P(T) = \begin{cases} \prod_{i=1}^{N} P(X_i) \ for\ AND\ Gate \\ 1 - \prod_{i=1}^{N} \{1 - P(X_i)\} \ for\ OR\ Gate \end{cases} \tag{6.6}$$

To calculate P(T), Relyence software has been used. Relyence software is a robust platform for constructing FT diagrams, modelling input events, and performing a variety of calculations to determine the probability of undesirable events and the combination of contributing factors that would lead to these undesirable events (Abuelrub et al., 2021). Using the probabilities of failure of the basic events as inputs, the obtained probability of failure of the top event, i.e., the failure of precision agriculture implementation is computed.

6.2.5 Calculating the importance of the basic events leading to the failure of the top event

Fault tree importance measures give a quantitative method for identifying risk reduction opportunities in Fault Tree Analysis (FTA). These importance measures assist in targeting those events that are likely to have the most impact on improving your system's overall performance metrics, such as availability and reliability. The probabilistic importance (also known as Birnbaum's measure) is defined as the rate of change in the system's total probability in response to changes in the probabilities of the BEs (Miziula and Navarro, 2019). It is a measurement of the functional margin of the BE system. Table 6.4 shows the probabilistic importance of the basic events in the fault tree. The measure considers the probability of each component failing and the consequences of that failure on the overall system. The probabilistic importance of a component in the fault tree is then calculated based on the combination of these probabilities and consequences. It also considers the probability of each possible failure scenario in the fault tree, considering the probability of each

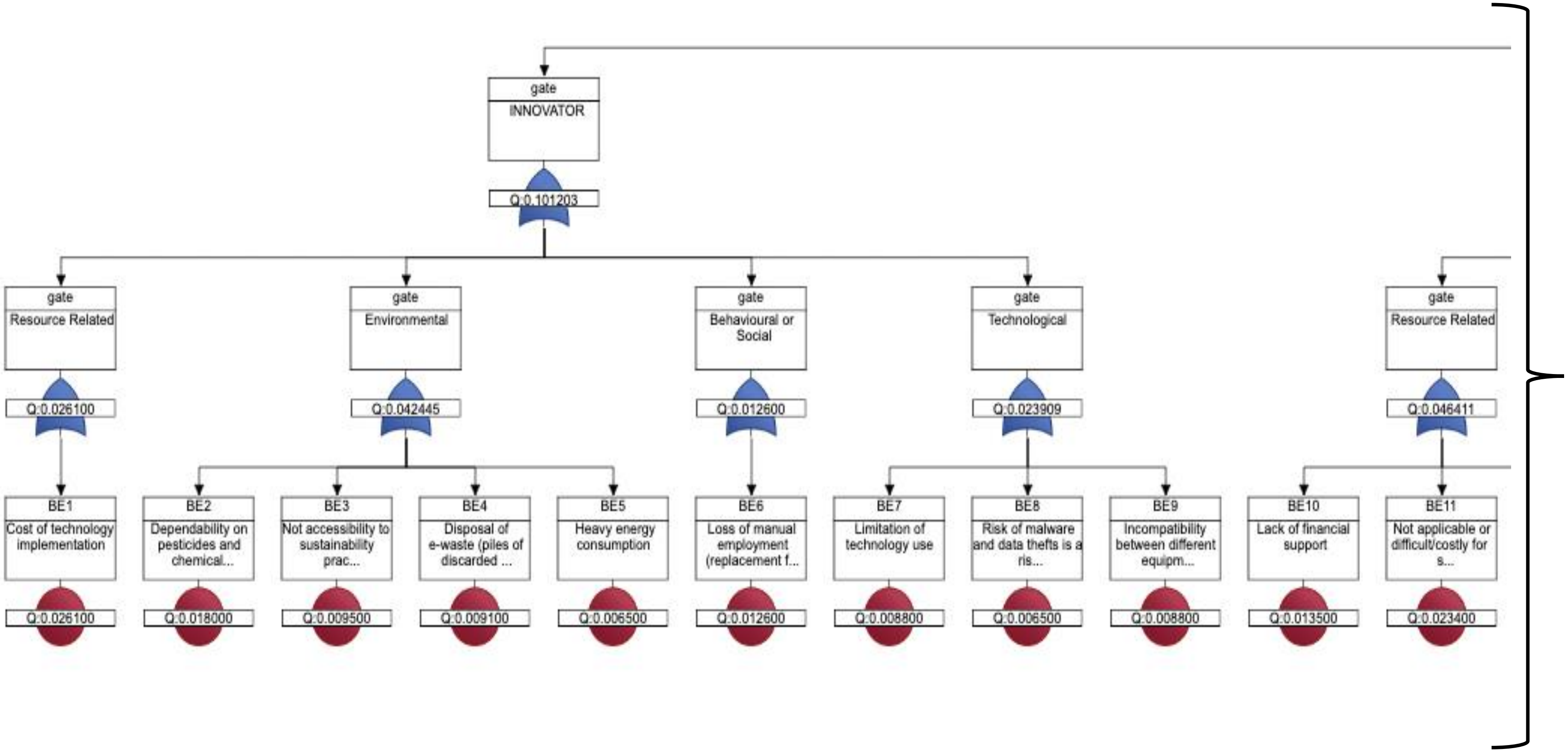


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Fig. 6.3 Overview of the attack fault tree to estimate the failure of probability

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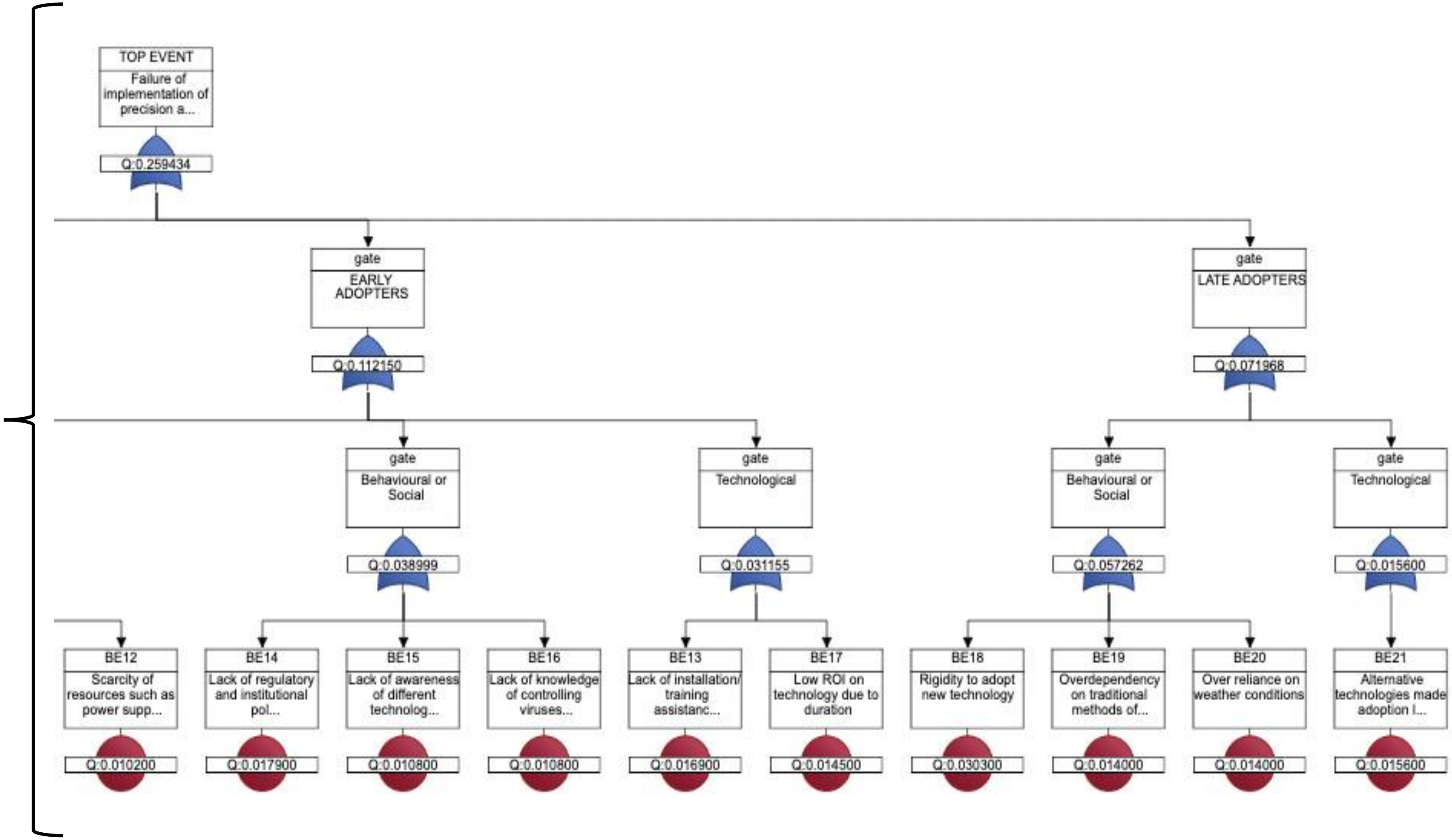


Fig. 6.3 Overview of the attack fault tree to estimate the failure of probability

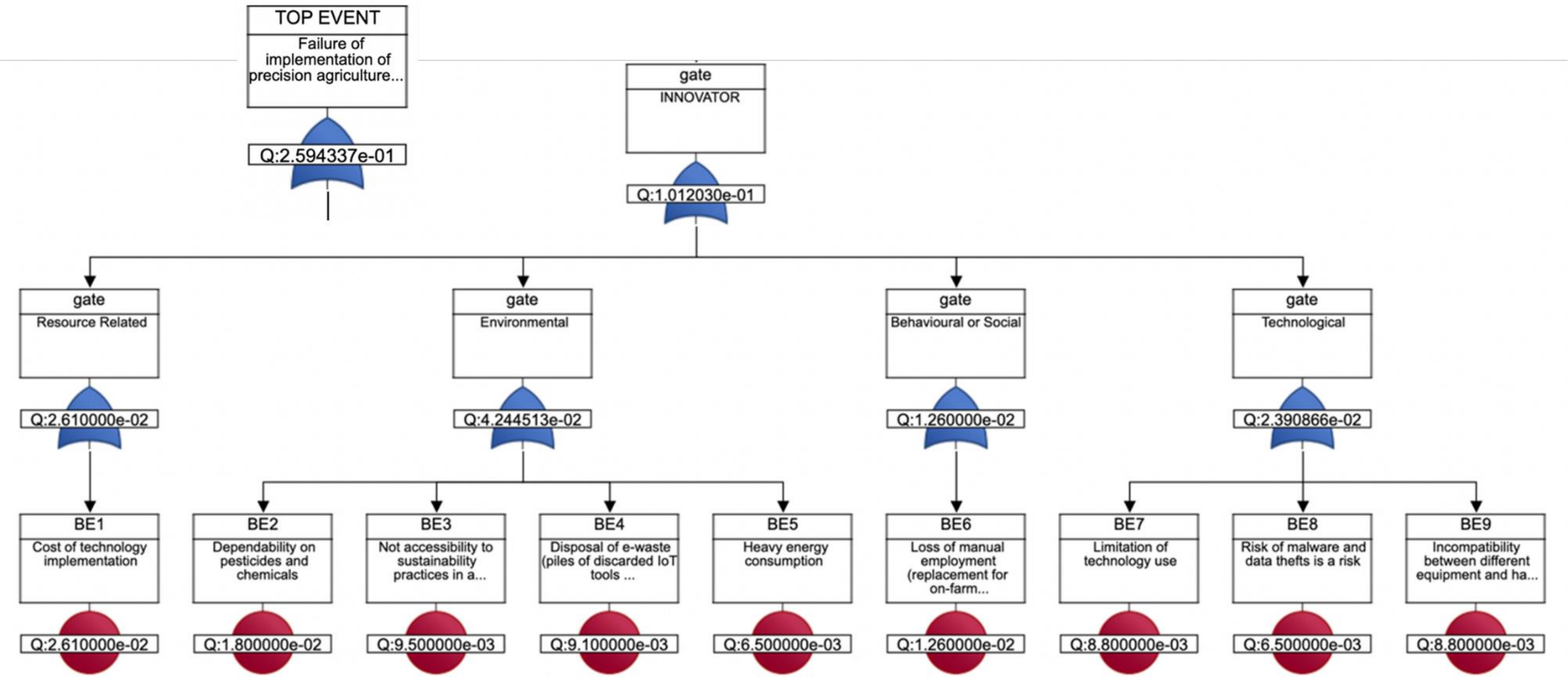


Fig. 6.4 Top event and Innovators' logic gate with events and their probabilities of failure

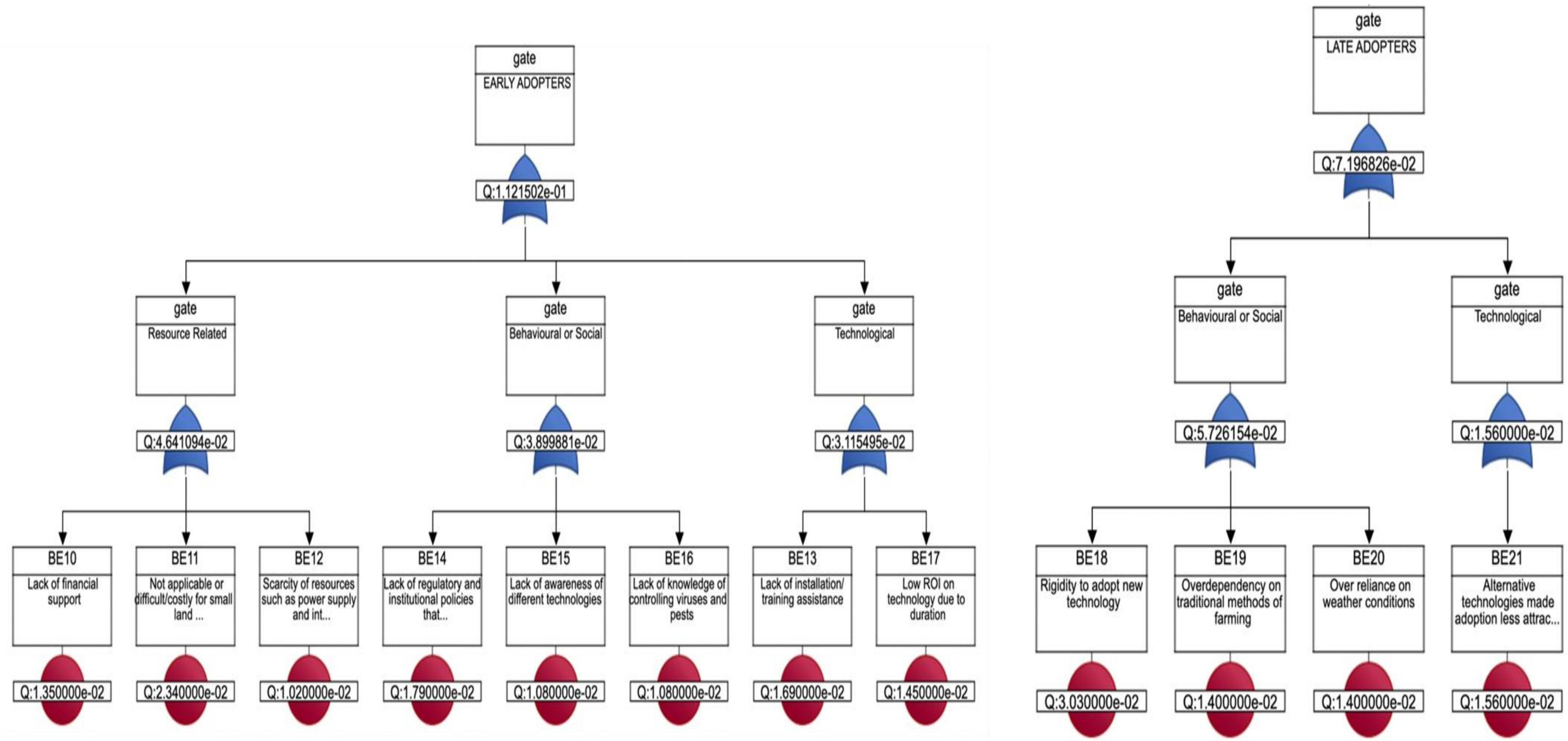


Fig. 6.5 Early and Late Adopters' logic gate with events and their probabilities of failure

component failing and the relationships between the components. The probabilistic importance (PI) is determined using equation (6.7):

$$PI(X_i) = \frac{\partial P(T)}{\partial X_i} \tag{6.7}$$

Table 6.4 Probabilistic importance of the basic events

Basic Event	PI	Rank of PI	Basic Event	PI	Rank of PI
BE1	0.7604	2	BE12	0.7482	15
BE2	0.7541	4	BE13	0.7533	6
BE3	0.7477	16	BE14	0.7541	5
BE4	0.7474	17	BE15	0.7487	13
BE5	0.7454	20	BE16	0.7487	14
BE6	0.75	12	BE17	0.7515	8
BE7	0.7471	18	BE18	0.7637	1
BE8	0.7454	21	BE19	0.7511	9
BE9	0.7471	19	BE20	0.7511	10
BE10	0.7507	11	BE21	0.7523	7
BE11	0.7583	3			

6.3 Results and Discussions

6.3.1 Outcomes of innovators' analysis

Innovators are often the first adopters of emerging technologies. They take risks, have widespread acceptance, and collaborate closely with other innovators. Results indicate that (Fig. 6.6a), innovators mostly face environmental issues (45%) such as high dependability on pesticides and chemicals, not having accessibility to sustainable practices in agriculture, disposal of E-waste and heavy energy consumption due to the operation of the smart sensors and other gadgets. These outcomes can in accordance with previous studies. Due to the modernization of agriculture and excessive consumption of fertilizers and chemical pesticides, immense amount of soil has been destructed and eroded in each hectare in different countries (Far and Rezaei-Moghaddam, 2017). According to innovators, their access to sustainable agricultural practices such as alternative energy, permaculture, hydroponics and aquaponics, polycultures and crop rotation, and local markets for their produce is limited.

The lack of access to such methods has influenced their output and the expense of implementing precision agriculture technologies (Soma et al., 2019). Another concern faced by the innovators is that if smart farms become the norm, each unit of "smart" food will have a far larger technology footprint than in the past due to e-waste and manufacturing embodied energy. (Streed et al., 2021). The deployment of video surveillance (one of the techniques in precision agriculture) to take, process, and broadcast images to the base station over the agricultural regions may indicate excessive energy use (Anisi et al., 2015).

The Basic Events 1 to 9, i.e., BE 1 to BE 9 are the challenges listed in the questionnaire, which are faced by the innovators. Fig. 6.6b. shows that for BE 1, i.e., cost of technology implementation, three out of the eight experts feel that implementation cost is very high. Similar results were obtained by Kendall et al. (2017) which shows that the adoption of precision agriculture in China was hampered by high costs, a lack of benefits that were perceived, and the necessary skills and abilities. Three out of the eight experts feel that BE 2, i.e., dependability on pesticides and chemicals is very high since agrochemical production has significantly increased as a result of modern agricultural growth. Consequently, pesticides are a necessary component of modern life agriculture (Maksymiv, 2015). For the other basic events, none of the experts hasn’t rated the factors as ‘very high’. The cost of implementation of precision agriculture practices and dependability on pesticides and chemicals seem to be an important factor for the experts. This is also confirmed in Fig. 6.6d. where we can see that BE 1 and BE 2 contribute most to the failure of the top event with scores of 0.7604 and 0.7541 respectively.

Fig. 6.6c represents the expected vs the current status of implementation of the precision agriculture techniques suggested by the scientists. It can be inferred that BE 1, i.e., cost of implementation is most likely to get failed out of all the other basic events with a maximum failure probability score of 0.0261. This validates the fact that cost is the most important factor contributing to the failure of the implementation of precision agriculture techniques as indicated by Fig. 6.6d. This also verifies the discussion that the investments in precision agriculture farm equipment may require loans or change the farm business's financial structure, which may have an impact on both labour costs and other capital expenditures (Schimmelpfennig, 2018). According to the study conducted by D’Antoni et al. (2012), the high cost of investment was identified by farmers as 334 a significant obstacle to the adoption of precision agriculture. When asked if they would like to use these technologies, 10.3% of farmers said no, citing the high investment cost as a hindrance to adoption. Additionally, for farmers who may already be operating on thin margins, the high cost of implementing precision agriculture can be a deterrent to adoption. Additionally, the cost of maintaining and updating the equipment and software used in precision agriculture can also be a burden for some farmers. As a result, the cost of implementing PAT can be a hindrance to its adoption, particularly for farmers who may not have the financial resources to invest in these technologies. Similarly, dependability on pesticides and chemicals (0.7541) and loss of manual employment (0.7500) seems to be crucial in implementing the PATs on the ground.

Fig. 6.6d. represents the contribution of the basic events towards the failure of the top event, i.e., the failure of the implementation of the precision agriculture techniques. The basic events are ranked on the basis of their Birnbaum importance measure. The maximum loss in system reliability caused by a component going from perfect working to a certain failure is represented by the Birnbaum importance ranking. It is an interval risk importance metric, totally reliant on the system model's architecture and unrelated to the current probability of the fundamental event. Since the BE 1 has the highest importance measure, i.e., 0.7604, this signifies that it is the most critical to the innovators' gate. The probability of the failure of the innovator gate in the fault tree is 0.101203 as shown in Fig. 6.4, which is more than that of the late adopters, i.e., 0.071968 as shown in Fig. 6.5. indicating that issues faced by innovators should be addressed on priority with respect to the late adopters. Innovators can also play a crucial role in driving innovation and progress within an industry or field. By being the first to adopt and experiment with new technologies or ideas, innovators can help to identify and solve problems, create new opportunities, and pave the way for more widespread adoption. As a result, they can often be more influential and important in driving change and advancement within a given field (Diederen et al., 2003).

6.3.2 Outcomes of early adopters' analysis

Farmers that belong to the early adopter category start using technology after a certain time period. Early adopters experience adoption much more slowly than innovators does. Results indicate (Fig. 6.7a), both behavioural/social and resource-related issues (38%) are mostly faced by the early adopters and environmental concerns are not being faced by them currently. These issues are lack of financial support, the precision agriculture practices not applicable or difficult/costly for small land holdings and scarcity of resources such as power supply and internet access, lack of regulatory and institutional policies that promote both a national and international agenda for precision agriculture adoption, lack of awareness of different technologies and lack of knowledge of controlling viruses and pests. These outcomes are in accordance with previous studies. The problem of inadequate education extends over and above farmers, as shown by the decrease in funding for educational initiatives (Ofori and El-Gayar, 2021). Training and financial assistance are important for precision agriculture implementation in farms. These two factors are directly connected to the barriers described above (costs and lack of knowledge) (Ammann et al., 2022). Another factor involved in the failure of implementation is that with present digital technology, applying precision agriculture techniques on a farm of fewer than 2 hectares offers little economic value (Erickson and Fausti, 2021) Additionally, because using the internet demands certain skills, a lack of those skills may only exacerbate the differences already observed across farmers. This is crucial given the lack of resources about the internet in the native languages of the farmers. (Mehrabi et al., 2021) Growing disparities in the availability of sustainable irrigation supply services, in particular groundwater and power, have taken centre stage in several recent global development discussions (Chaudhuri et al., 2021). There are several programmes aimed at advancing agriculture. In terms of boosting productivity, cutting costs, or raising price realisation, there aren’t efficient delivery systems that can transform things into efficient implementation on the ground. Inadequate government assistance makes these problems worse (Yadav et al., 2015). The majority of Indian farmers are illiterate, and they have little access to information that might enable them to research the methods for reducing pest attacks.

The Basic Events 10 to 17 are the challenges listed in the questionnaire which are faced by the early adopters. Fig. 6.7c indicates that for BE 11, i.e., precision agriculture techniques are not applicable or difficult/costly for small land holdings. Four out of eight experts feel that this is a very important factor contributing to the failure of precision agriculture implementation on the ground (Fig. 6.7b). This can also be validated by previous research (Babu, 2013) which talks about how precision agriculture has not previously been utilised by farmers with small and marginal holdings, particularly those in developing countries, in the setting of open farms-especially homestead farms. Three out of the eight experts (Fig. 6.7b) feel that BE 12, i.e., scarcity of resources such as power supply and internet access play a very crucial factor in the implementation of PATs since the strongest effect on precision agriculture adoption is the perceived extent of resources available (Aubert et al., 2012). For BE 14, i.e., lack of regulatory and institutional policies that promote both a national and international agenda for precision agriculture adoption, 3 out of 8 experts rated this a very

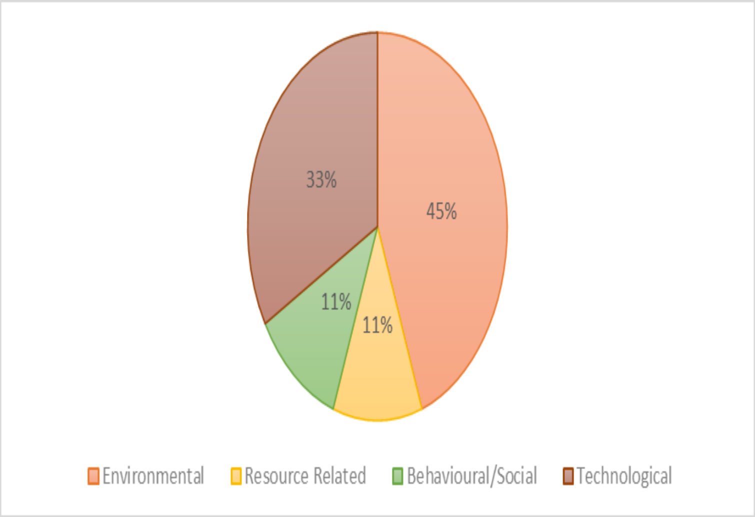


Fig. 6.6a Issues faced by innovators

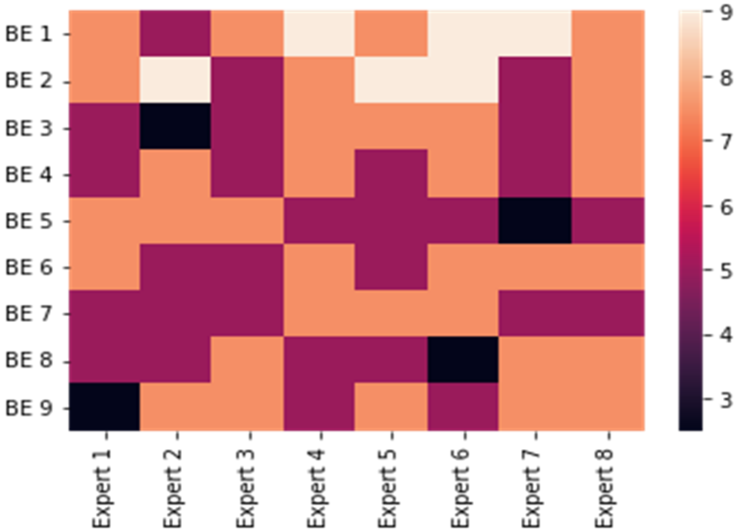


Fig. 6.6b Heatmap showing the responses of experts

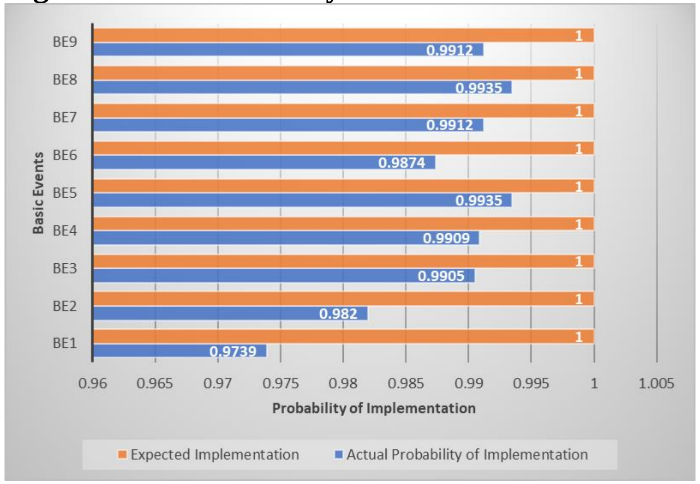


Fig. 6.6c Expected vs current status of implementation of precision agriculture techniques for innovators

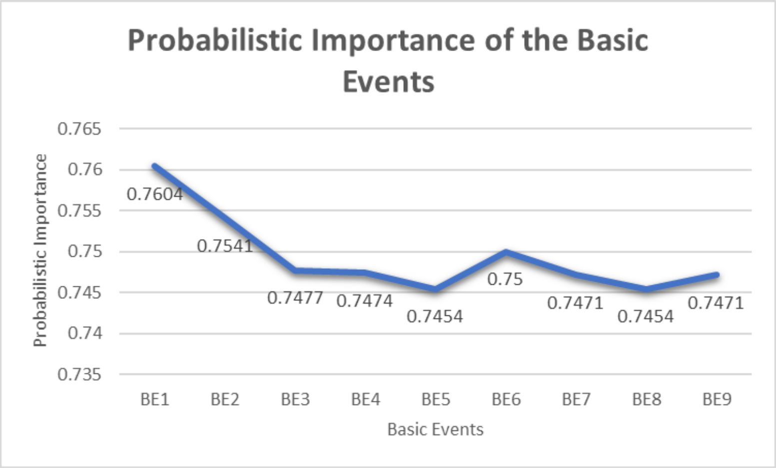


Fig. 6.6d Contribution of the basic events towards the failure of the top event for the innovators

important factor in the implementation of PATs since national agricultural policies have one of the most influential impacts on precision agriculture adoption (Mizik, 2022). Lastly, for BE 17, i.e., low return on investment (ROI) on technology due to duration, 3 out of the 8 exerts feel that this factor is also very important because according to (White et al., 2021), the absence of a distinct ROI provides the biggest barrier to the implementation of data-intensive technologies on farms. For the other basic events, none of the experts hasn't rated the factors as 'very high'. Small land holdings, scarcity of resources, lack of government/institutional policies and low return on investments seem to be important factors for the experts. This is also validated by Fig. 6.7d. where BE 11, BE 14 and BE 17 contribute most to the failure of the top event with probability scores of 0.758, 0.754 and 0.751 respectively.

Fig. 6.7c. represents the expected vs the current status of implementation of the precision agriculture techniques suggested by the scientists. It can be inferred that BE 11, i.e., precision agriculture techniques are not applicable or difficult/costly for small land holdings is most likely to get failed out of all the other basic events. The failure probability of the event is 0.0234 which is more than the other basic events. This supports the discussion that land area is one of the most important factors contributing to the failure of the implementation of precision agriculture techniques in Fig. 6.7c. This also validates the analysis carried out in this chapter that small farms often find it harder to profit from the benefits of economies of scale from innovations. (Tamirat et al., 2018). Similarly, lack of training and installation assistance (B13) and a lack of government policies (B14) that promote precision agriculture adoption seems to be important in implementing the PATs suggested by the scientists in the farms with failure probability scores of 0.753 and 0.754 respectively.

Fig. 6.7d. reflects the role that the basic events played in the failure of the top event (on-ground implementation of precision farming techniques). The Birnbaum significance metric is used to rank the basic events. The BE 11 is the most crucial component for the early adopters' gate because it has the greatest importance measure (0.758). The probability of the failure of the early adopters' gate in the fault tree is the highest among all, i.e., 0.112150 (Fig. 6.5) indicating that issues faced by early adopters should be addressed on priority with respect to the other two categories of farmers. While finding the factors contributing the most to the top event, the factor that precision agriculture techniques are not applicable or difficult/costly for small land holdings has an overall rank of 3, implying that a precision agriculture management typically depends on physical work when applied to extremely small landowners. (Erickson and Fausti, 2021).

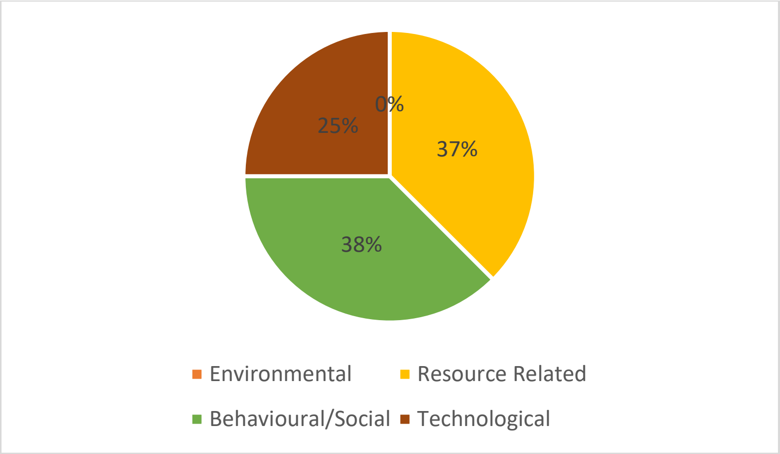


Fig. 6.7a Issues faced by the early adopters

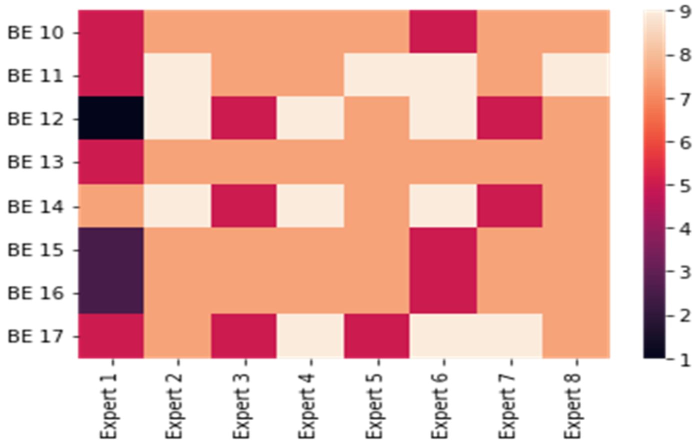


Fig. 6.7b Heatmap showing the responses given by experts

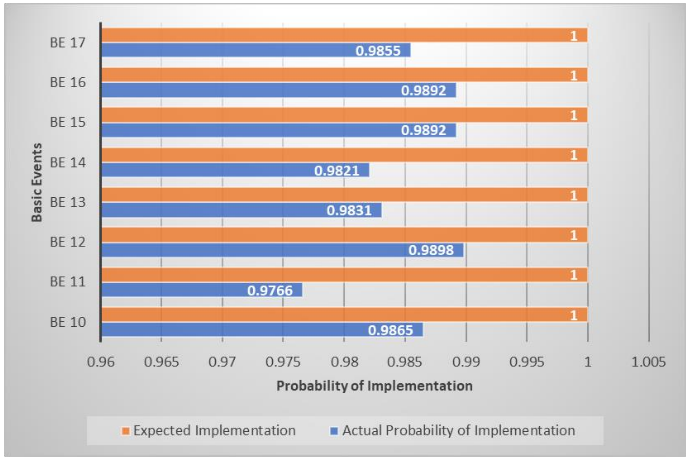


Fig. 6.7c Expected vs current status of implementation of precision agriculture techniques for early adopters

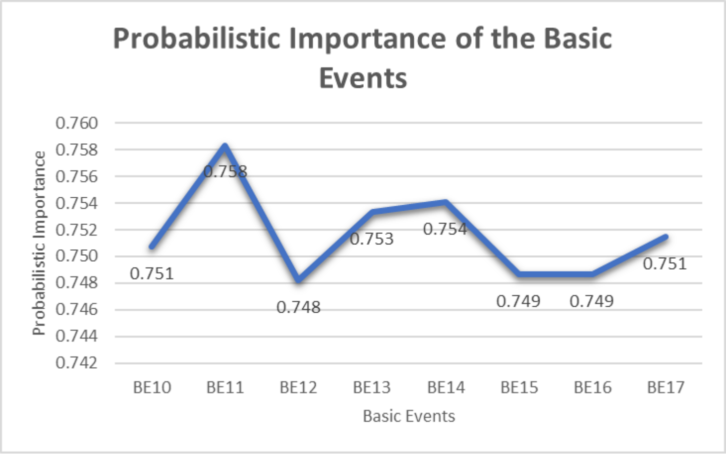


Fig. 6.7d Contribution of the basic events towards the failure of the top event for the early adopters

6.3.3 Outcomes of late adopters' analysis

Late adopter farmers have demonstrated little or no interest in current farming methods. They dislike change and think that new technologies will be a waste of time and resources that won't help them. Fig. 6.8a indicates that behavioural/social issues are mostly faced by the late adopters (75%), and they currently do not face environmental and resource-related issues. These issues are rigidity to adopt new technology, overdependency on traditional methods of farming and overreliance on weather conditions. Traditional farming techniques predominate in Indian agriculture. The same agricultural methods have been used for generations. Precision farming adoption is predominantly hampered by resistance and rigidity (Katke, 2019). Total dependency on weather conditions for farming has led to the aggravation of the problems of late adopters (Soma et al., 2019).

The Basic Events 18 to 21 are the challenges listed in the questionnaire which are faced by the late adopters. Fig. 6.8b shows that for BE 18, i.e., rigidity to adopt new technology, four out of eight experts feel that farmers are too rigid to adapt the PATs suggested by the scientists due to the stubborn traditions attached to agriculture (Patil et al., 2013). Three out of the eight experts feel that BE 19, i.e., overdependency on traditional methods of farming is very high since the farmers continue to utilise traditional crop-growing techniques that do not produce high yields and carry a significant risk of failure while ignoring a superior alternative in the form of technology-based agriculture since the notion of precision agriculture is not widely adopted (Katarya et al., 2020). Again, BE 20, i.e., over-reliance on weather conditions, seems to be an important factor for the experts since the farmers are overly dependent on imprecise historical data and costly weather stations (Foughali et al., 2018). For BE 21, i.e., alternative technologies made adoption less attractive, two out of the eight experts feel that this is a very important factor in determining the failure of the PATs. There exist technologies like Global Navigation Satellite Systems, LiDAR Sensors and Thermal Cameras Systems which can make adoption of PATs less attractive and feasible (Romero-Gelvez et al., 2020). This is also validated by Fig. 6.8d. where we can see that BE 18 contribute most to the failure of the top event with a score of 0.7637.

Fig. 6.8c shows the expected implementation of PATs on the ground vs the current status of implementation of the precision agriculture techniques as suggested by the scientists. It can be inferred that BE 18, i.e., rigidity to adopt new technology is most likely to get failed out of all the other basic events. The failure probability of the event is 0.0303 which is more than the other basic events. This supports the discussion that rigidity and resistance towards a new form of agriculture are one of the most important factors contributing to the failure of the implementation of precision agriculture techniques as shown in Fig. 6.8d. Similarly, alternative technologies seem to be a crucial factor in the on-ground implementation of PATs. Fig. 6.8d reflects the role that the basic events played in the failure of the top event, which was the precision agriculture adoption by the farmers as suggested by the scientists. The Birnbaum importance measure is used in the system to rank the basic events. The BE 18 is the most important factor for the late adopters' gate because it has the greatest importance measure (0.7637).

The probability of the failure of the early adopters' gate in the fault tree is the lowest among all, i.e., 0.071968 (Fig. 6.5) indicating that issues faced by the late adopters, in general, do not pose a major challenge to the precision agriculture techniques suggested by the scientists and their on-ground implementation on the farmlands by farmers. While finding the factors contributing the most to the top event, the factor of rigidity to adopt new technology has an overall rank of 1, confirming the discussion that Indian farmers are prevented from implementing technology in their agricultural practices due to their resistance to change and belief in old and traditional practices of farming. Numerous public and private sector initiatives to increase precision agriculture adoption in agriculture have not yielded the desired results in terms of awareness and adoption (Edukemy, 2021).

6.3.4 On-ground implementation of precision agricultural techniques using proposed approach

Fuzzy fault tree analysis was used to analyse and evaluate the potential challenges or risks associated with a given system or process. In the context of precision agriculture, this approach can help the local governmental bodies to guide/train the farmers in identifying potential challenges or obstacles to the successful implementation of precision agriculture techniques on the ground. For illustration, if a farmer wants to implement precision agriculture techniques in his farm, the first step in the fuzzy fault tree analysis process would be to identify the potential challenges or obstacles that the farmer might face. For example, some common challenges associated with precision agriculture in India include the availability of suitable technologies, the cost of implementing these technologies, and the need for specialized knowledge and skills.

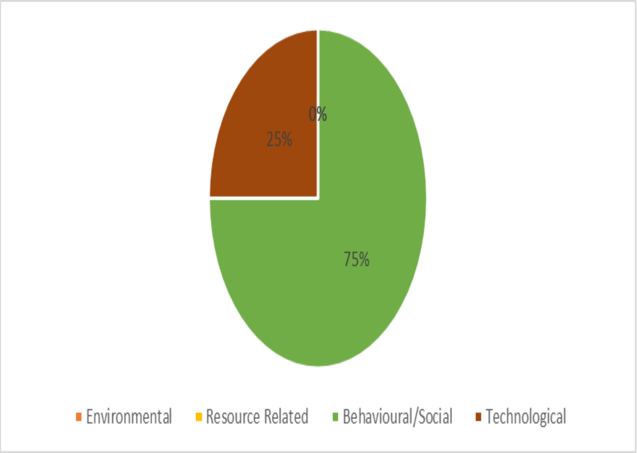


Fig. 6.8a Issues faced by the late adopters

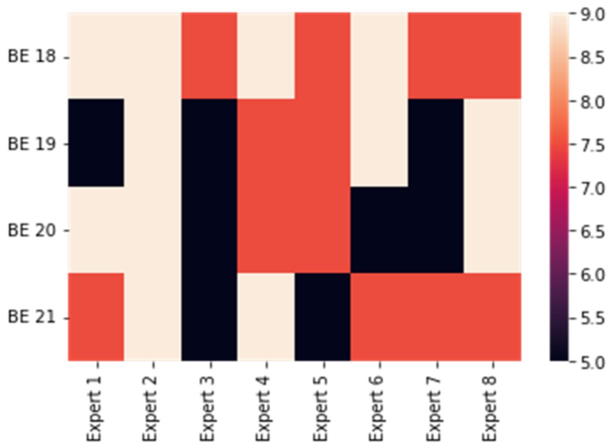


Fig. 6.8b Heatmap showing the responses given by experts

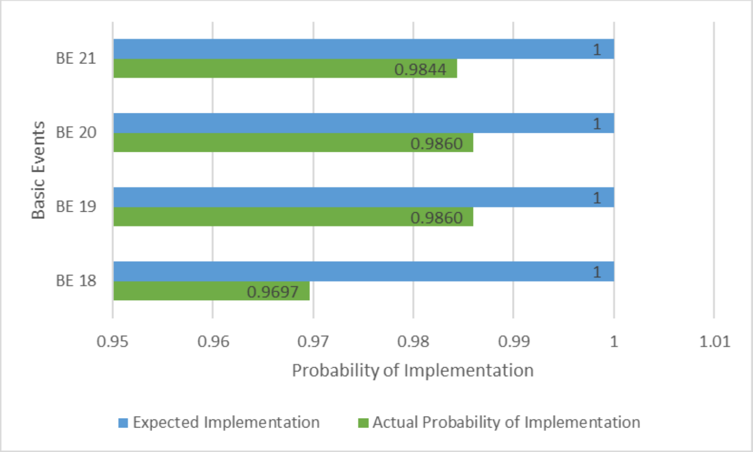


Fig. 6.8c Expected vs current status of implementation of precision agriculture techniques for late adopters

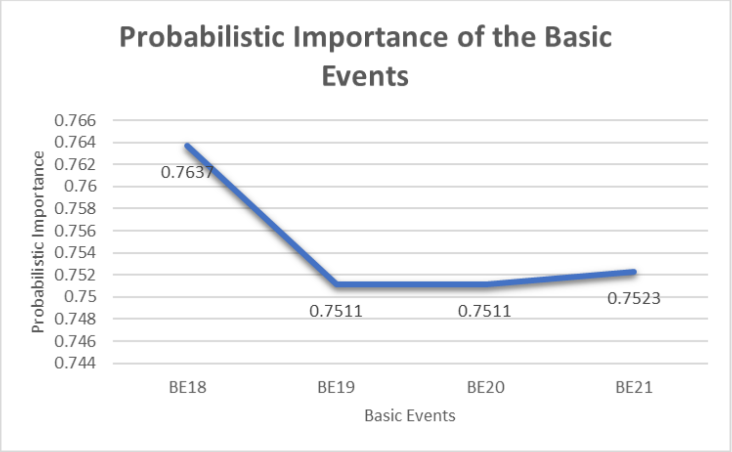


Fig. 6.8d Contribution of the basic events towards the failure of the top event for the late adopters

Once the potential challenges have been identified, the next step would be to evaluate the likelihood and impact of each challenge. This can be done using fuzzy logic, which allows for the representation and manipulation of uncertain or imprecise information. In this case, the local bodies might use fuzzy logic to assign a likelihood value to each challenge, based on farmer's experience and knowledge, expert judgement, and historical data of the specific obstacles they are likely to face. Once the likelihood and impact of each challenge have been evaluated, the next step would be to analyse the fault tree, which is a graphical representation of the potential challenges and how they are related to one another. It also helps the farmer to calculate the likelihood of the top event occurring. This can help the farmer to identify potential risk factors and prioritize their efforts to overcome these challenges.

For example, the farmer might identify that the availability of suitable technologies is a key factor in the success of their precision agriculture efforts, and therefore focus their efforts on acquiring the necessary technology. Alternatively, the farmer could collaborate with other farmers or government organizations to pool resources and collectively purchase the necessary technology. This could help to reduce the individual cost for each farmer, and also provide opportunities for sharing knowledge and expertise. Another option would be for the farmer to seek out partnerships with technology providers or other organizations that could provide access to the necessary technology. This could include arrangements such as rental agreements or lease-to-own options, which could help to make the technology more affordable for the farmer. Finally, the farmer could also explore government programs or initiatives that provide support for the adoption of precision agriculture technologies. These programs could provide funding, technical assistance, or other resources that could help the farmer access the necessary technology.

Fig. 6.9, which shows how the proposed approach can be a useful tool for identifying and addressing the potential challenges associated with the implementation of precision agriculture techniques. By providing a structured, step-by-step approach to evaluating and mitigating these challenges, the outcomes can help farmers successfully implement precision agriculture techniques on the ground and achieve their desired outcomes. Additionally, this approach is universally applicable and can be used by farmers in any region or location, regardless of their specific challenges or obstacles.

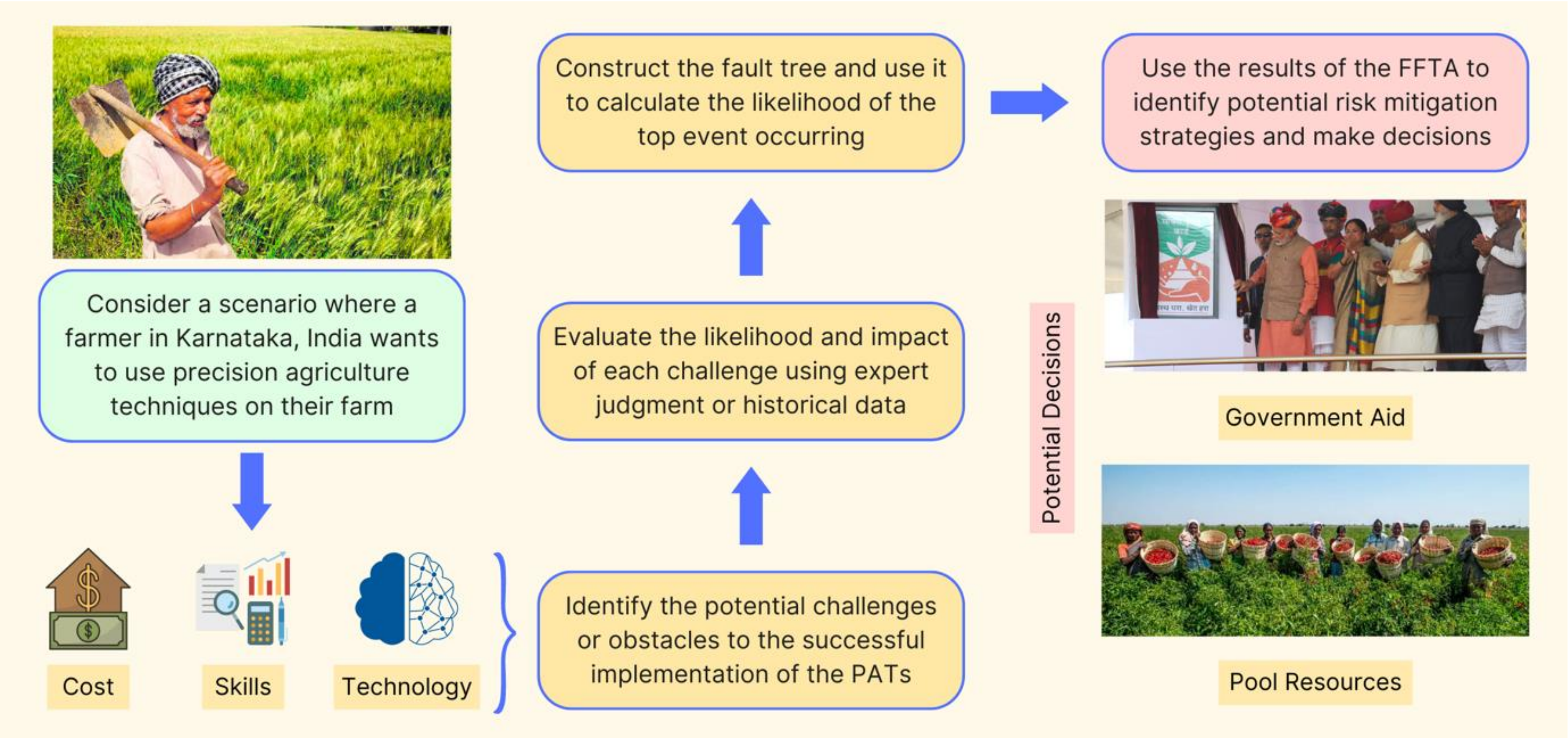


Fig. 6.9 Demonstration of how the proposed approach can be implemented by a farmer or local governmental bodies.

6.4 Summary

Precision agriculture is a dynamic, technology-driven management system. They enable farmers to swiftly address a wide range of issues, including fertiliser runoff, crop diseases, and declining yield. Today, the impact of precision agriculture techniques can be observed globally. Despite its popularity, ground truthing reveals that environmental, socio-economic, and technological challenges prevent the broad adoption of precision agriculture. Thus, this chapter aims at bridging the gap between the precision agriculture techniques suggested by the technically sound practitioners and their on-ground implementation using fuzzy fault tree analysis. The study covers two aspects: (i) it employs expert elicitation and fuzzy logic approach for estimating the failure probability of precision agriculture implementation, and (ii) it incorporates uncertainties into the data obtained from various stakeholders using fuzzy fault tree analysis (Fig. 6.10).

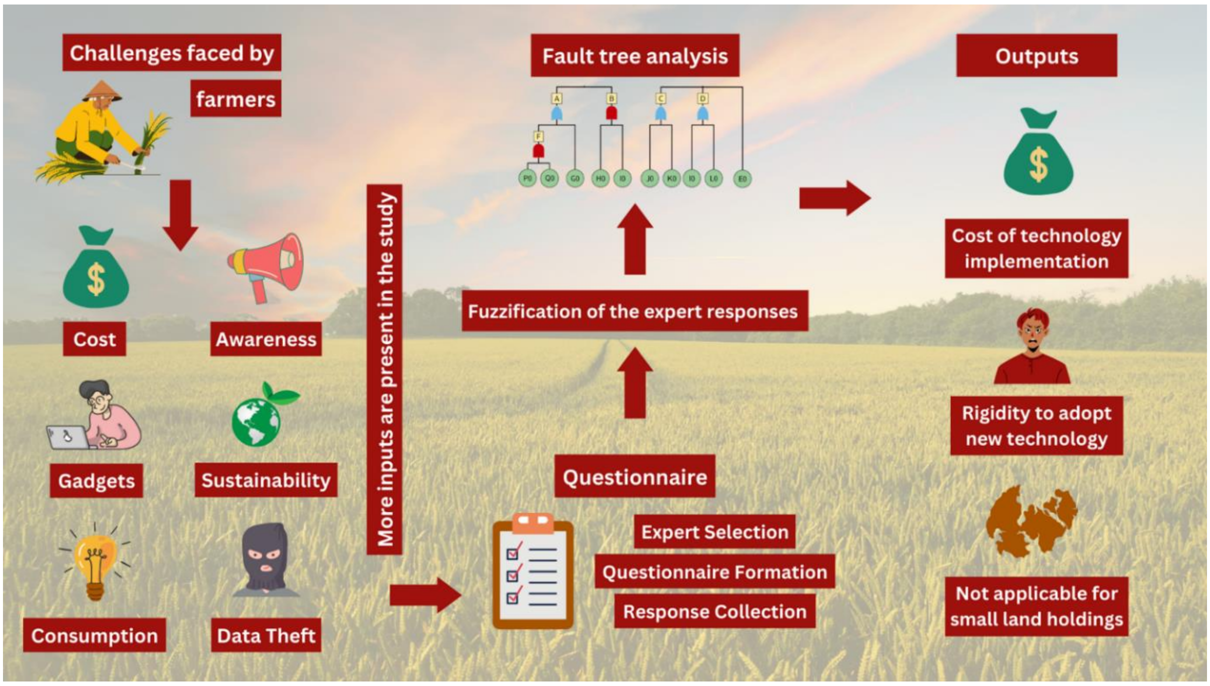


Fig. 6.10 Summary of the fuzzy fault tree analysis technique for identifying the key challenges to precision agriculture adoption.

The outcomes of this study indicate that rigidity of adopting new technology, cost of technology implementation and difficulty of implementation for small land holdings are the major challenges to precision agriculture as their probabilistic importance measures (also known as Birnbaum's measure) are 0.763, 0.760 and 0.758 respectively.

This chapter would provide researchers, academicians, local communities, scientists and farmers with a comprehensive research guide for the implementation of precision agriculture practices. The upcoming chapters analyse and learn from the cutting-edge technology/Best Management Practices (BMPs) for ANPS pollution control from the United States using a couple of novel approaches and deliberate their applicability for the Indian watersheds (particularly Muzaffarnagar, Uttar Pradesh). These approaches allow integration of several BMPs, i.e., these techniques do not limit the use of a single control strategy (either Source or Process or End control strategy for control of NPS pollution) but consider or amalgamates the use of control strategies from each of these domains and renders a cost-effective set of practices to achieve maximum pollution reduction. The next chapter expands the use of complex modelling software - HSPF to even amateur modelers by advancing the use of a Scenario Application Model (SAM) that not only render such analysis effective, but also significantly simplifies the on-field targeting of conservation practices thus widening their adoption and control of non-point source pollution.

CHAPTER 7

ADVANCED AND SIMPLIFIED AGRICULTURAL DECISION SUPPORT FOR COST-EFFECTIVE MANAGEMENT OF CONSERVATION PRACTICES

7.1 Introduction

The Muzaffarnagar study area considered in the earlier chapters has fertile agricultural land (alluvial soils) driving more than 40% of its population in agriculture with about 75% of district's land area apportioned for agriculture. The district is known for its intensive farming practices and significantly contributes to the countries' GDP while simultaneously discharging disproportionate nutrients to the vital Ganga/Yamuna Rivers deteriorating water quality and ecosystem health. The Mississippi River basin in the USA has significant parallels with the selected study area in India such as fertile land (alluvial soils), intensive agriculture supporting the regions' economy, and extensive nutrient runoff from agricultural fields in the Mississippi River causing considerable issues in the Gulf of Mexico. However, the USA has made significant advancements in the comprehensive control of ANPS pollution through establishing various regulations such as Clean Water Act and their facilitating their enforcement via various state agencies like Environmental Protection Agency (EPA). Apart from this, there are numerous innovative BMPs, and effective implementation strategies practiced by USA. The present chapter is aimed at evaluating a simplified and effective approach in implementing these practices and simultaneously study and learn the conservation strategies from the US watersheds.

The hypoxic zone in the Gulf of Mexico, furthered by the excess of nutrients (nitrogen and phosphorus), is increasing by an average of four thousand square miles every summer (USEPA, 2015). The landscape conversions, predominantly the substitution of freshwater wetlands for agricultural lands, is one of the major contributing factors responsible for this upsurge in hypoxic space (Drake et al., 2018). The strategical field scale implementation of conservation practices (CPs) or the best management practices (BMPs) for reducing nutrient export has been recognized as a promising approach for curbing such unintended episodes (Tomer et al., 2013; Rundhaug et al., 2018; Qiu et al., 2019; Srinivas et al., 2020). However, the inaccurate selection of location, type, and often the extent to which BMPs should be applied not only prove ineffective in handling ecological impairments, but also increases the financial stress on management authorities. Concurrently, the simultaneous interaction of various fields encompassing land use, hydrology, agriculture, climate, terrain, soil type, and incorporation of viewpoints of various stakeholders (farmers, policy makers, research scientists) etc., makes it challenging to ascertain a meaningful selection and placement of cost-effective BMPs.

To comprehensively evaluate and suggest effective solutions or to direct the decision-making processes, various/multitude of watershed-scale models such as Prioritize, Target, and Measure Application (PTMApp), Agricultural Conservation Planning Framework (ACPF), BASINS, Environmental Policy Integrated Climate - Agricultural Policy/Environmental eXtender (EPIC-APEX), Soil and Water Assessment Tool (SWAT) (Srinivas et al., 2022; Rallapalli et al., 2022) and integrated tools/systems have been developed (Liu et al., 2016; Yuan et al., 2020), extensively reviewed, and compared in the scientific studies (Fu et al., 2019; Srinivas et al., 2020; Yuan et al., 2020; Lee et al., 2023), with most intended to review models targeting specific metrics such as the geographical locations; the systems models cater, i.e., coastal or urban; or based on their modeling aspects, e.g., parameterization, spatial and temporal scales. The watershed modelling approaches has already been discussed in detail in the section 2.3 in the 2nd Chapter of synthesis. Amongst all other models, Hydrologic Simulation Program Fortran (HSPF) has been widely adopted for catchment-scale water quality modeling (Fu et al., 2019; Yuan and Koropeckyj-Cox, 2022).

Watershed modeling scientists across the globe have extensively used HSPF to assess the nutrient fate and transport in lakes and rivers and the pollution generated from various landscapes and point sources. HSPF could simulate both urban and agricultural watersheds at a timescale ranging from a few minutes to centuries and at a spatial scale from a few acres to massive watersheds (Tadesse Sinshaw et al., 2022). Despite having extensive applicability and wide-scale adoption, these models like HSPF, have inherent modelling limitations, for example, it necessitates additional adjustment of numerous physical parameters and non-physical parameters i.e., pure calibration parameters (Rajat and Athira, 2021). Similarly, calibration and validation processes of HSPF involve the parameterization of several parameters, which renders the simulation time-intensive and demands trained users or modeling expertise (Duda et al., 2012; Sarkar et al., 2019). HSPF is advantageous in modeling pollutant transport processes for producing large datasets that give simulated pollutant loadings at watershed outlets. However, the complex modeling interface of HSPF limits a decision maker of a practitioner from taking advantage of these features. Practitioners or governmental bodies, need a moderately technical and easily understandable tool, which can help them design various optimized BMP scenarios for meeting TMDL goals in an economical and timely manner under different agro-climatic conditions. Instead of themselves interpreting the outputs of these models for further decision analysis, practitioners often pay huge amounts to third party modelers to do this job for them. Not only HSPF, other conventionally popular models like SWAT and EPIC-APEX also lack the ability to offer a flexible space to the practitioners to swiftly develop BMP scenarios and perform watershed planning depending on budget constraints and farmers preferences. There is a great need to develop a platform to transform the complex outputs of these models into useful outcomes such as TMDL achievement goals under different economic setups, BMP planning and design based on farmer’s inputs, climate variations.

This chapter addresses these problems by evaluating the efficacy of HSPF Scenario Application Manger (SAM), which facilitates or extends the utility of HSPF simulation results by providing an interactive and spatial decision support tool. In particular, the study aims to (i) design and simulate alternative scenarios with SAM and develop cost optimized scenarios based on user-defined water quality targets, and (ii) simplify complex hydrologic modeling applications into transparent estimates of pollutant sources while allowing stakeholders (primarily farmers) to apply their local knowledge and expertise of watershed planning and implementation. Using SAM, the non-modeling watershed management personnel can also estimate the effect of conservation practices on downstream water quality and thus, develop cost-effective TMDL scenarios and Watershed Restoration and Planning Strategies (WRAPS).

7.2 Materials and methods

7.2.1 Study area

Pomme de Terre watershed, stretched over 2264 km^2 of land area, has majority of the land area (74%) apportioned for agriculture (primarily cropland and pasture, where corn, soybean, spring wheat, and alfalfa are the principal crops). The Pomme de Terre (PdT) River is divided into two parts, with lower unit of the watershed having a gradient almost double that of the upper unit. The headwater region (upper Pomme de Terre watershed), located in the west-central part of Minnesota, is known for sustaining both aquatic life and recreation, and for providing the best quality waters through its streams and lakes. However, moving down the watershed, the landscape and land use transform primarily from lakes, wetlands, and forests to croplands, thus impairing the river water quality by escalating the nutrient concentrations levels (MPCA, 2011).

Drywood Creek watershed (Fig. 7.1), situated in the southwest part of Pomme de Terre watershed, is one such cropland-dominating unit (with about 75% of cropland). Also, Drywood Creek, alongside Muddy Creek and Pelican Creek, is one of the main tributaries of the Pomme de Terre River mainstream. Hence, it has been selected as the representative region (study area) for the Pomme de Terre watershed. The Drywood Creek enters Pomme de Terre River south of Morris and contributes its maximum nitrate-nitrite nitrogen levels in April and maximum phosphorus during April and July months, ultimately discharging into the Minnesota River situated below Marsh Lake. Along with high nutrient transfer, this creek also exacerbates turbidity and dissolved oxygen levels. The nutrient increase in the Minnesota River also contributes to hypoxia in the Gulf of Mexico. Therefore, the present study is an effort toward providing a cost-effective nutrient management approach by developing TMDL scenarios and suggesting suitable practices using HSPF-SAM.

7.2.2 Key features of HSPF based SAM model

HSPF is a continuous, comprehensive, and semi-distributed tool that models the hydrological processes and water quality components at a watershed scale (Chen et al., 2019). The simulation results of the model provide time history sequences for nutrient and sediment loads and water quality and quantity for the entire watershed. The pervious and impervious land surfaces' hydrological and water quality process simulation in HSPF is performed under PERLND and IMPLND modules. HSPF simulates numerous water quality constituents such as biological oxygen demand (BOD), dissolved oxygen (DO), sediments, nitrate, phosphate, pesticides, phytoplankton, etc. (He and Hogue, 2012). However, the sediment and phosphorus, are selected as the two major water quality components in this study pertaining to their high concentrations in the Dry Wood creek which are well beyond permissible limits. HSPF simulates the sediment and phosphorus constituents using the SEDMNT and PQUAL section of its PERLND application module which on the other hand simulates network of water quality and quantity processes taking place on the pervious land stretches. SEDMNT simulates the sediment runoff through two different processes namely, the direct soil transport from the land surface (i.e., scour), given by the Eq. 7.1,

$$\mathrm{V} = \left(\frac{S_O}{(S_O+S_S)} \times K_S \times \left(\frac{(S_O+S_S)}{t}\right)^{E_S} \times t\right) \tag{7.1}$$

where,

V = scour of soil mass (tons/ac/interval)

$K_S =$ scour coefficient

$E_S =$ scour exponent

$S_S =$ surface water storage (inches)

$S_O =$ surface outflow of water (in/interval)

and secondly, by washing off of the soil particles (T in tons/acre/interval) accumulated or detached from the land surface via winds, rainfall, and anthropogenic interferences, etc.

The capacity of the overland flow to transport the detached sediment (C in tons/acre/interval) is first computed using equation 7.2,

$$\mathrm{C} = \left(\frac{(S_O + S_S)}{t}\right)^{E_D} \times K_D \times t \tag{7.2}$$

where:

$K_D =$ detached sediment transport coefficient

$E_D =$ detached sediment transport exponent

which is then compared with the detached sediment available (D in tons/acre) for transportation, i.e., if C > D then the detached sediment transported is computed using the equation 7.3,

$$\mathrm{T} = \left(\frac{S_O}{S_O + S_S}\right) \times D \tag{7.3}$$

While in case of sufficient availability of the detached sediment equation 7.4 is exercised,

$$\mathrm{T} = \left(\frac{S_O}{S_O + S_S}\right) \times C \tag{7.4}$$

While the PQUAL module simulates the water pollutants such as nitrogen, phosphorus, dissolved oxygen, etc. available on pervious land stretches through four different pathways viz. pollutant available on the land surface; pollutant associated with the soil mass; pollutant in the interflow and outer flow. For instance, the simulation of pollutants removed by the overland flow from the land surface is as described the following equation 7.5,

$$G = \left(A + M_O \times \left(1 - \frac{A}{M_{inf}}\right)\right) \times \left(1 - e^{-S_O \times \frac{2.3}{R}}\right) \tag{7.5}$$

where,

G = pollutant wash off from the land surface (unit/ac/interval)

$A =$ pollutant accumulation rate (unit/ac/day)

$M_O =$ quantity of pollutant available on land surface at interval beginning (unit /acre)

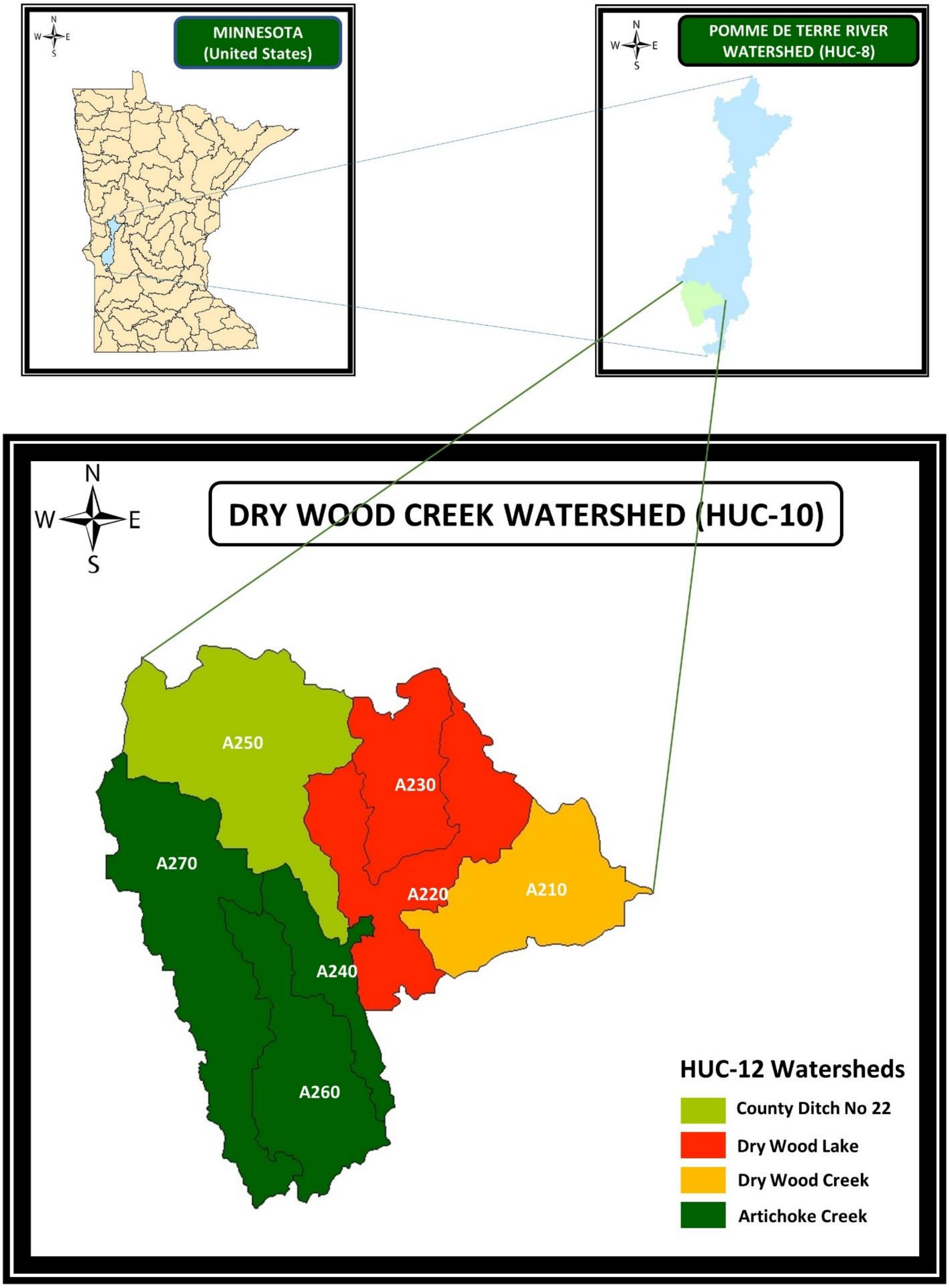


Fig. 7.1 Dry Wood Creek watershed and its sub-watersheds' location in the United States

$M_{inf} =$ quantity of pollutant at infinite time, if no washoff happens (unit /acre)

$S_O =$ surface outflow of water (in/interval)

R = surface runoff rate for 90% washoff in one hour (in/hr)

The HSPF model also aids the impact assessment of various conservation practices by improvising changes to the model inputs. However, the complex modeling interface of the HSPF model makes it challenging for non-modeling users/local governmental personnel to evaluate the impacts of these strategies using field scale knowledge (RESPEC, 2022). To develop watershed restoration and protection strategies, governmental agencies need to develop economically sound TMDL scenarios, and also a detailed plan to achieve TMDL goals through the medium of most suitable BMPs.

The Scenario Application Manager (SAM), built on the MATLAB platform, has been developed based on the HSPF model results. The results of alternative models can also be very well tailored into a format compatible with SAM. SAM comprises a geographical information system-based interface for HSPF model applications. It overcomes the limitations of the HSPF model by allowing non-modelers users to estimate the pollution sources in a simplified manner enabling them to use their local knowledge and watershed planning expertise (RESPEC, 2022). The utility modules of SAM encompass project description, watershed analysis, designing BMPs and TMDL scenarios, and targeting cost-effective BMPs. Under the project utility, scenarios designed in the SAM project are managed. ‘Analyze’ analyses the various simulated scenarios obtained through HSPF. ‘Design’ offers an array of alternatives to customize the management scenarios. It offers a total of 26 different BMPs (some listed in Table 7.1). While the ‘Target’ enables users to ascertain a cost-optimized management scenario for the desired water quality goals. One of the unique features of SAM is its ability to incorporate uncertain opinions of the farmers and local watershed experts into the model for proposing BMPs and their priorities. The project package or the database concerning HSPF results for the Pomme de Terre watershed (Hydrologic Unit Code (HUC) -8) watershed, comprising the basic HSPF model application files converted into the SAM project, has been retrieved from an online platform (RESPEC, 2022) supported by Minnesota’s Clean Water Legacy Fund.

Table 7.1 The brief description of the conservation practices supported by SAM

BMPs	Purpose
Nutrient Management	Prevention or reduction of nutrients (Nitrogen and Phosphorus primarily) impacts on water quality by managing the source, placement, time, and application rate of fertilizers, manure, etc.
Restored Tiled Wetlands	Restored wetlands could improve the water quality, natural habitat, and landscape
Tile Line Bioreactors	Reduces nitrate-nitrogen concentration from agricultural subsurface drainage through denitrification
Controlled Tile Drainage	Addresses soil productivity by managing or regulating the agricultural subsurface drainage flow
Riparian Buffers	Interception of runoff, pesticides, stream bank erosion through grasses, forbs establishment between upland and aquatic habitats
Filter Strips	Removal of overland flow contaminants using an herbaceous vegetation strip area
Conservation Crop Rotation	Reduces undue runoff, and soil erosion and improves soil fertility by growing strategic cropping sequences
Conservation Cover Perennials	Maintenance of permanent vegetative cover reduces soil erosion and improves water quality
Corn & Soybeans with Cover Crop	Control of soil erosion, water quality improvement, and increase in plant productivity through the plantation of grass, forbs as seasonal vegetative cover

BMPs	Purpose
Short Season Crops with Cover Crop	Control of soil erosion, water quality improvement, and increase in plant productivity through the plantation of grass, forbs as seasonal vegetative cover
Reduced Tillage	Increases water infiltration in soils, thus preventing erosion, nutrients transport to streams by restricting activities which disturbs soil
Alternative Tile Intakes	Prevents ponding and increases soil productivity by conveying excess water
Corn & Soybeans to Rotational Grazing	Improves soil, animal, and plant health by allowing animals to grazing
Water and Sediment Control Basin	Traps sediments and detains water through a constructed ridge/embankment across marginal waterway slopes
Constructed Stormwater Pond	Detains and can help regulate stormwater runoff, removes pollutants through gravitational particulate settlement

7.2.2.1 Brief description of model

In this study, the functions of SAM have been systematically utilized to develop a flexible decision support system for watershed planning and restoration. The schematic procedure has been explained in Fig. 7.2. The detailed discussion on SAM has been provided in its manual (RESPEC, 2022). The primary functions of SAM include ‘Project, Analyze, Design and Target’. The ‘Project’ function provides information on the loaded SAM project and manages the project scenarios. The study area map and data pertaining to Drywood Creek Watershed for the time period (1996-2016) was utilized by this function to perform watershed analysis. The ‘Analyze’ function was used to analyse and export the sediment, phosphorus and flow data to calculate reach concentration, reach load, source load, source load rate, basin load, basin load rate, basin source load, basin source load rate, source fate contribution, and basin fate contribution. Design function developed tailored model scenarios for handling nutrient transfer based on prespecified BMPs, land use changes, point source alternatives, and climate change predictions. This function was also used to consider the percent suitability of land, i.e., the percent land in the selected basin where the BMP in question has already been installed, thus not available for its implementation.

Also, the uncertain opinions of the farmers have been included using 'farmer participation' level, which signifies the percentage of farmlands where it is favourable to adopt a particular BMP. The default efficiencies of the BMPs related to flow, total phosphorus, and total sediment were taken for intermediate (5-10 years) and long term (10-20 years) time period. Similarly, the default costs assigned to each practice were based on local knowledge and the 2016 Minnesota NRCS EQIP (Natural Resources Conservation Service Environmental Quality Incentives Program) cost-share docket for Minnesota. A detailed description of default efficiencies and the costs can be found in Kenner et al. (2017) and Pease et al. (2007). However, the efficiencies and cost of BMPs are generally subjective to the factors like metrological conditions, soil properties, terrain, implementation techniques, etc. The practitioners equipped with the knowledge and/or in consultation with experts can determine these efficiencies and can modify these costs and efficiencies in SAM. Before finalizing or developing the design scenario, the time series inputs of climate components: temperature, and precipitation, were adjusted by opting for one of the three predefined levels of climate change predictions, i.e., mild, moderate, and severe.

Finally, the Target function optimizes the allocation of BMPs to achieve the target loading for the targeted reach within the specified budget. This function was applied by selecting the target reach to which the target threshold would be set. Then, the target limit for the selected parameter and annual budget restriction was specified. The function provides the design or the discernment of BMPs on which optimization would be practiced. The practitioner can either add practices previously added or develop a new set of BMPs for building an optimization scenario.

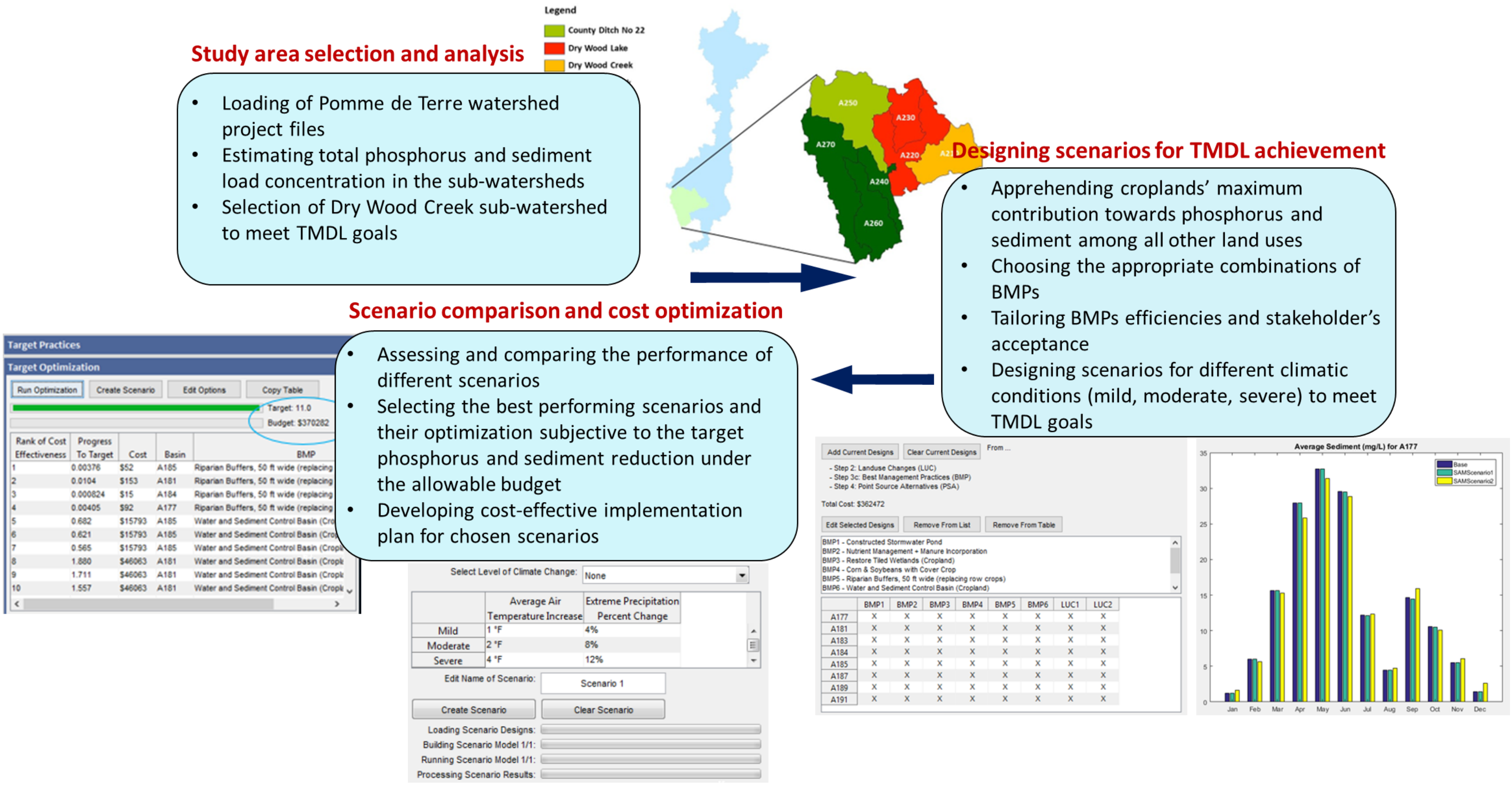
The BMP allocation optimization constraints encompassing the pollution/load reduction and the available budget were obtained using the PdT river watershed TMDL report published by the Minnesota Pollution Control Agency (MPCA) (MPCA, 2011). The report delivers the permissible loading capacity to address the impairments of a PdT river tributary, Dry Wood Creek, and four lakes in the PdT watershed. Finally, it suggests the general cost estimate for treating primarily turbidity and phosphorus-related impairments in waterbodies, as mentioned above, amounting to around $ 6 million. Since the majority of the seven selected practices are simultaneously effective for reducing both the phosphorus and the turbidity loads, and except for the Dry wood creek, the TMDLs are provided for the phosphorus loads only, the total budget is segregated into 6 parts (one for each: PdT river tributary, Dry Wood Creek, and four lakes) based on the amount of phosphorus required to be removed from each of these resources. The apportion of the total budget for Dry Wood Creek thus comes to around 85%, i.e., \$ 5.1 million. The TMDL limit for phosphorus and sediment load for Dry Wood Creek is 7.5 kg/day and 1190 kg/day, respectively, and the average total phosphorus and average sediment load worked out from January 1996 to December 2016 using SAM is 27.9 kg/day and 2880 kg/day.

7.3 Findings from HSPF-SAM based analysis

7.3.1 Pollution loadings in the Dry wood creek watershed

Using SAM, the study analysed the basin load for the total phosphorus, which was found to be ranging from 88.32 kg/year (Tenmile lake watershed) to 6541.8 kg/year (Judicial Ditch No. 2 watershed), and the total annual sediment load variation was observed to be 8910 kg (Tenmile lake watershed) to 31,90,000 kg (Pomme de Terre River watershed). The Dry Wood Creek watershed (Fig. 7.1), containing four different HUC-12 units: County Ditch No. 22, Dry Wood Lake, Dry Wood Creek, and Artichoke Creek, has been considered to identify the optimized set of practices for attaining recommended TMDL provided by the MPCA PdT watershed TMDL report (MPCA, 2011). The estimated phosphorus and sediment loads in the selected reach(s) result from various land uses in the watershed are presented in Table 7.2 and 7.3. The contribution from the point sources such as ‘septic tanks’ has been neglected (less than 1%). The Artichoke Creek sub-watershed among other sub-watersheds contributes maximum towards phosphorus load which could be true because of the largest land area in this sub-watershed.

Also, the cropland (high and low till) being the major land use (occupying 75% of the land area) contributes more than 95% and 90% towards phosphorus in the Dry Wood Creek watershed. Hence, the BMPs recommended in the upcoming sections pertain to cropland land use. The last two rows (Total and Total Reach load) in Table 7.2 and 7.3 shows the accumulated phosphorus load across all land uses in the given sub-watershed and the transfer of these loads to their respective basin reaches. Similar results have been observed related to the sedimentation loading. It could be noted that this load transfer value for phosphorus is consistently lower than the accumulated load generated in Artichoke Creek, County Ditch No



Study area selection and analysis

- Loading of Pomme de Terre watershed project files
- Estimating total phosphorus and sediment load concentration in the sub-watersheds
- Selection of Dry Wood Creek sub-watershed to meet TMDL goals

Designing scenarios for TMDL achievement

- Apprehending croplands’ maximum contribution towards phosphorus and sediment among all other land uses
- Choosing the appropriate combinations of BMPs
- Tailoring BMPs efficiencies and stakeholder’s acceptance
- Designing scenarios for different climatic conditions (mild, moderate, severe) to meet TMDL goals

Scenario comparison and cost optimization

- Assessing and comparing the performance of different scenarios
- Selecting the best performing scenarios and their optimization subjective to the target phosphorus and sediment reduction under the allowable budget
- Developing cost-effective implementation plan for chosen scenarios

Target: 11.0
Budget: $370282

Rank of Cost Effectiveness	Progress To Target	Cost	Basin	BMP
1	0.00376	$52	A185	Riparian Buffers, 50 ft wide (replacing
2	0.0104	$153	A181	Riparian Buffers, 50 ft wide (replacing
3	0.000824	$15	A184	Riparian Buffers, 50 ft wide (replacing
4	0.00405	$92	A177	Riparian Buffers, 50 ft wide (replacing
5	0.682	$15793	A185	Water and Sediment Control Basin (Cro
6	0.621	$15793	A185	Water and Sediment Control Basin (Crop
7	0.565	$15793	A185	Water and Sediment Control Basin (Cropl
8	1.880	$46063	A181	Water and Sediment Control Basin (Cropl
9	1.711	$46063	A181	Water and Sediment Control Basin (Cropl
10	1.557	$46063	A181	Water and Sediment Control Basin (Cropl

Select Level of Climate Change: None

	Average Air Temperature Increase	Extreme Precipitation Percent Change
Mild	1 °F	4%
Moderate	2 °F	8%
Severe	4 °F	12%

Edit Name of Scenario: Scenario 1

- Step 2: Landuse Changes (LUC)
- Step 3c: Best Management Practices (BMP)
- Step 4: Point Source Alternatives (PSA)

Total Cost: $362472

BMP1 - Constructed Stormwater Pond
BMP2 - Nutrient Management + Manure Incorporation
BMP3 - Restore Tiled Wetlands (Cropland)
BMP4 - Corn & Soybeans with Cover Crop
BMP5 - Riparian Buffers, 50 ft wide (replacing row crops)
BMP6 - Water and Sediment Control Basin (Cropland)

	BMP1	BMP2	BMP3	BMP4	BMP5	BMP6	LUC1	LUC2
A177	X	X	X	X	X	X	X	X
A181	X	X	X	X	X	X	X	X
A183	X	X	X	X	X	X	X	X
A184	X	X	X	X	X	X	X	X
A185	X	X	X	X	X	X	X	X
A187	X	X	X	X	X	X	X	X
A189	X	X	X	X	X	X	X	X
A191	X	X	X	X	X	X	X	X

Fig. 7.2 A synoptic overview of the SAM model application

22, and Dry Wood Lake, whereas there is a shift in this trend for the Dry Wood Creek sub-watershed. Land uses like forest and grassland contribute only minutely to pollution and therefore, could be considered as the potential alternatives for converting croplands.

Table 7.2 Total annual phosphorus load and source areas in Dry Wood Creek watershed basins

Landuse ↓ Watershed →	**Artichoke Creek (kg|km^2)**	**County Ditch No 22 (kg|km^2)**	**Dry Wood Lake (kg|km^2)**	**Dry Wood Creek (kg|km^2)**
Developed	211.5|4.3	121.28|2.43	124.5|2.44	66.8|1.29
Forest	8.27|1.04	3.8|0.47	5.4|0.64	3.2|0.37
Cropland High Till	4493.1|36.35	5867.52|46.3	5543.2|42.37	2711.8|20.24
Cropland Low Till	2781.7|29.02	0|0	670.3|6.78	747.8|7.36
Grassland	20.24|1.9	4.9|0.45	4.7|0.42	7.2|0.62
Pasture	33.08|1.3	16.3|0.64	13.5|0.51	46.4|1.74
Wetland	103.9|18.24	23.3|4.02	42.1|6.59	9.9|1.49
Developed EIA	9.07|0.26	5.3|0.15	4.9|0.14	2.6|0.073
Feedlot	9.53|0.06	0|0.04	16.6|0.03	16.2|0.03
Total	7670.3|92.44	6042.4|54.5	6425.3|59.92	3611.9|33.22
Total Reach Load	**6896**	**5205**	**7244**	**10183**

7.3.2 BMP selection and scenario development

The reduction of sediment and phosphorus loads at the outlet of the Dry Wood Creek watershed has been evaluated by exercising the efficiencies of several BMPs applicable to the given watershed. A total of 7 BMPs (Table 7.4) have been selected in consultation with watershed authorities, experts, and a literature survey (Arne, 2013; MPCA, 2013, 2011; Srinivas et al., 2020). To develop a base scenario, the participation level from the farmers (i.e., the degree to which they are willing to adopt a particular practice) has been set to a default value of 50% for all BMPs. The default 'reference suitability factor', a factor which accounts for the percent by which a particular BMP is suitable for the land area under consideration, has also been assigned to the selected BMPs. These values have been retrieved from the recent records of BMPs in the HUC-12 regions of Minnesota. The efficiencies of the practices, in general, reduce with time

(Liu et al., 2017). Therefore, a predefined set of efficiencies of the BMPs for phosphorus and sediment reduction have also been incorporated pertaining to the time frame or the years for which BMPs are expected to function.

Table 7.3 Total annual sediment load in Dry Wood Creek watershed basins

Landuse ↓ Watershed →	**Artichoke Creek (1000 × kg)**	**County Ditch No 22 (1000 × kg)**	**Dry Wood Lake (1000 × kg)**	**Dry Wood Creek (1000 × kg)**
Developed	62.82	34.48	33.99	17.68
Forest	0.04	0.01	0.02	0.02
Cropland High Till	418.43	583.07	549.38	256.31
Cropland Low Till	129.62	0	31.95	36.15
Grassland	1.04`	0.2	0.26	0.43
Pasture	3.6	1.49	1.4	4.78
Wetland	0.62	0.14	0.35	0.11
Developed EIA	8.36	4.64	4.45	2.4
Feedlot	1.27	0	1.92	1.86
Total	628.143	624.667	623.9404	331.549
Total Reach Load	**663.43**	**521.83**	**765.38**	**1055**

An intermediate range of 5-10 years has been selected for this study which commensurate with the time implied by the Minnesota Pollution Control Agency (MPCA) to achieve the TMDL. The default annual cost for per-acre implementation of BMPs has also been selected (Table 7.4). Finally, noticing the prevailing climatic conditions at the study location (MDNR, 2022), a mild level of climate change option has also been adopted (Appendix-A), which signifies a 1°F increase in average air temperature and a 4% change in extreme precipitation. Thus, in total seven scenarios were developed with each scenario having a single BMP. This approach was undertaken to assess the potential of each individual BMP in reducing both contaminants load, to understand their applicability, and cost efficiency. Table 7.4 shows that the nutrient management and manure incorporation, conservation crop rotation, and conservation cover perennials have high reference suitability percent of 99.3, 100, and 100 respectively and are thus applicable for almost all land parcels in the study watershed. While amongst these, conservation cover perennial renders the highest reduction factor (i.e., 0.96 and 0.84 for surface phosphorus and sediment reduction and likewise for inter and baseflow) and assumes the highest cost for (26,000 $/km^2/year).

Thus, it is expected to reduce the maximum load but also at the maximum cost. The other BMPs, like Water and Sediment Control Basin (WASCOBs), also have similar high load reduction factors (0.9 and 0.85 for surface phosphorus and sediment) and comparatively significantly lower costs (12,600 $/km^2/year) but could be applied only to the limited land parcels (i.e., ~ 20%). Thus, the distributed benefits of cost, applicability, and reduction potential among different BMPs emphasize that to achieve a cost-effective reduction in loads, we cannot rely on implementing a single practice in the entire watershed. Rather, a mix of practices must be taken into consideration (Jain and Singh, 2019; Xia et al., 2020).

Table 7.4 Best management practices scenarios and their specifications

Scenarios*	**BMPs#**	**Reference suitability percent**	**Reduction factor (Phosphorus/Sediment)**			**Cost($/acre/year)**
			Surface	**Interflow**	**Baseflow**	
1	NMMI	99.3	0.13/0	0.13/0	0.05/0	11.6
2	RB	19.2	0.8/0.9	0.68/0.9	0.46/0.9	23.4
3	FS	15.0	0.67/0.84	0.56/0.84	0.38/0.84	12.4
4	CCR	100	0.3/0.5	0.25/0.5	0.17/0.5	38.9
5	CCP	100	0.84/0.96	0.71/0.96	0.48/0.96	105.1
6	RT	20.3	0.68/0.8	0.57/0.8	0.38/0.8	10.0
7	Wascob	21.7	0.85/0.9	0.72/0.9	0.48/0.9	51.0

** For all scenarios, mild climate conditions are set (i.e., Avg. air temp. increase = 1^{o}F; Extreme precipitation % change = 4%)*

 # Nutrient Management and Manure Incorporation (NMMI); Riparian Buffers, 100 ft. wide (RB) Filter Strips, 50ft. wide (FS); Conservation Crop Rotation (CCR); Conservation Cover Perennials (CCP); Reduced Tillage (no-till) (RT); Water and Sediment Control Basin (Wascob)

7.3.3 Performance of scenarios in reducing phosphorus and sediment loading

Each of the selected BMPs (seven scenarios) was assessed independently in SAM to measure its potential against phosphorus and sediment reduction. Consequently, all four HUC-12 watersheds covering the entire Dry Wood Creek watershed in the Pomme de Terre (HUC-8), which contributes ultimately to the Dry Wood Creek, were applied with individual BMPs one after another, and the corresponding percent load reduction was observed using the ‘Target’ function in SAM (Figs. 7.3-7.4). The estimated costs required by each practice to achieve the indicated load reductions were also obtained through SAM and the efficiencies, i.e., parts per million of the ratio of percent load reduction to cost for each practice, were also determined. The ‘nutrient management and manure incorporation’ BMP shows fair phosphorus reductions, but it is not applicable for sediment reduction.

As evident from Figs. 7.3-7.4, the conservation cover perennial has excelled over all other practices with high margins, e.g., for the Dry Wood Creek sub-watershed, other practices could deliver at most 5.6% reduction in phosphorus load whereas conservation cover perennial could reduce 15.85%. Simultaneously, this practice exhibits the lowest efficiency of 1.24. On the other hand, the filter strips and reduced tillage encompass maximum efficiencies, i.e., 9.2 and 10.25 respectively, but they deliver poor load reductions. Thus, a tool that could allocate these practices to the basins while simultaneously considering their pros and cons, or in other words, a tool that can optimize the trade-off between load reductions and efficiencies of the practices while allocating them to the basins, is demanded. So, in the next section, an appropriately integrated optimization tool has been applied. Further, a general decline in phosphorus reduction for the BMPs could be observed (Fig. 7.3); like for conservation cover perennial Dry wood creek undergoes maximum percent reduction (15.85%) followed by Dry wood lake (14.76%), then County ditch no. 22 (12.61%) and Artichoke creek (5.15%) being the least. While in the case of riparian buffers and filter strips, County ditch no. 22 surpasses Dry wood lake. And an opposite trend is witnessed when the BMP is reduced tillage.

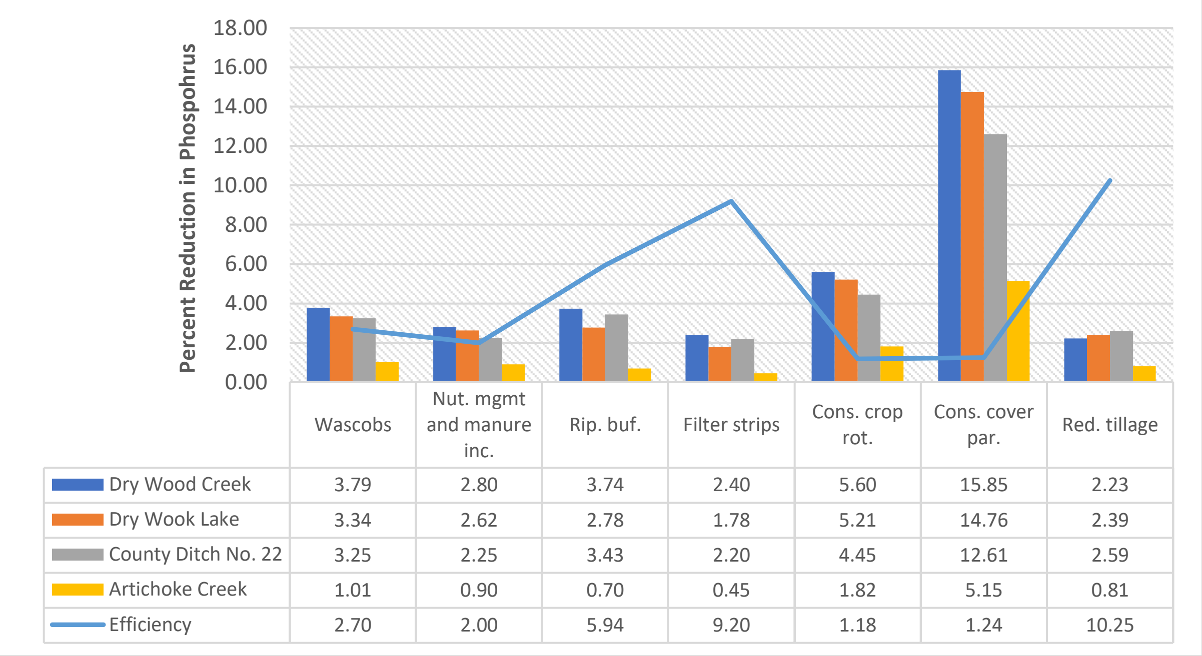
7.3.4 Optimized BMP allocation for attaining TMDL under economic constraints

The BMP allocation optimization constraints encompassing the pollution/load reduction and the available budget were obtained using the PdT river watershed TMDL report (MPCA, 2011). The general cost estimate for treating primarily turbidity and phosphorus-related impairments in waterbodies, as mentioned above, amounting to around $ 6 million. Since the majority of the seven selected practices are simultaneously effective for reducing both the phosphorus and the turbidity loads, and except for the Dry wood creek, the TMDLs are provided for the phosphorus loads only, the total budget is segregated into 6 parts (one for each: PdT river tributary, Dry

Wood Creek, and four lakes) based on the amount of phosphorus required to be removed from each of these resources. The apportion of the total budget for Dry Wood Creek thus comes to around 85%, i.e., $ 5.1 million. The TMDL limit for phosphorus and sediment load for Dry Wood Creek is 7.5 kg/day and 1190 kg/day, respectively, and the average total phosphorus and average sediment load worked out from January 1996 to December 2016 using SAM is 27.9 kg/day and 2880 kg/day. This sets out a 73.1% and 58.7% reduction in phosphorus and sediment loads as the second constraint for optimizing BMP allocation.

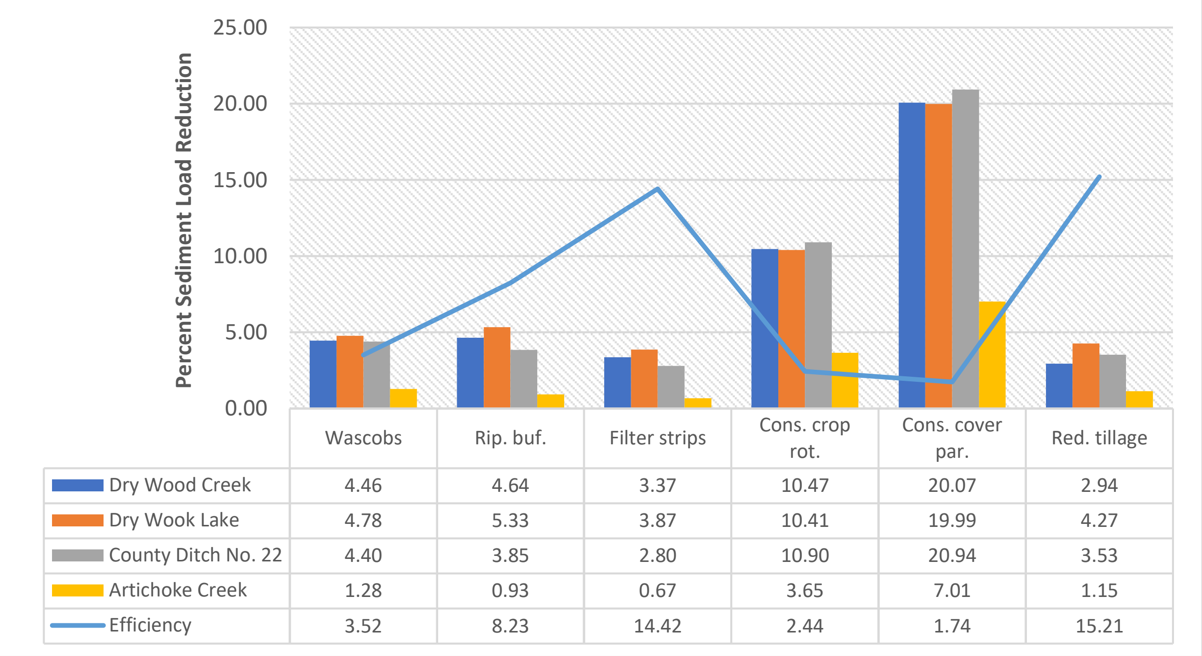
Using the designed practices discussed in the previous section and the 'Target' functions, five cases (Table 7.5) with integrated BMPs were generated to achieve the desired objectives (Tables in Appendix-A (A6 to A8) and Table 7.6). In the 1st Case, the four practices which showed higher reduction potential (i.e., NMMI, CCP, CCR, and Wascob) in the previous section were combined. Combinedly, these could attain the TMDL limits for phosphorus and sediment reduction (73.1% and 58.7%), but at almost 48.6% more cost ($ 7.58 million) than the allocated budget and at high landowner/farmer participation of 97.5%. To check the cost and to meet the TMDL, 2nd Case was run, keeping the farmer participation at 100% while replacing CCP and CCR with RB and FS. This Case delivered only a 34.25 % reduction in phosphorus, however, at quite a minimal relative cost of about $ 1.5 million.

This obliged that all 7 scenarios must be combined to meet the target reduction (73.1% for phosphorus and 58.7% for sediment) cost-effectively. Thus, in Case 3, an estimate of the total reduction potential, combining all 7 practices with a participation of 50%, was reckoned. A total of 52.5% reduction in phosphorus and a 65.1% reduction in sediment was achieved. As the reduction was not able to meet the TMDL limit for phosphorus (73.1%), to attain the desired reduction, several trials were run in the 4th Case by changing (increasing) the farmer participation level. At 83.7% of farmer participation, the desired reduction in phosphorus (73.1%) was achieved with an 83.4% corresponding reduction in the sediment load. However, the BMP allocations made in the 4th Case demand a budget of about $ 6.85 million (Table A8, Apppendix-A). Thus, the final (5th) Case was established, keeping the budget constraint at $ 5.1 million for phosphorus reduction, and a 71.1% reduction in phosphorus and 81.8% reduction in sediment loading resulted. The optimization also yields a HUC-12 watershed or basin-wise rank list of practices based on their efficiency (Table 7.6). Such a list is valuable as it prioritizes the BMP x



	Wascobs	Nut. mgmt and manure inc.	Rip. buf.	Filter strips	Cons. crop rot.	Cons. cover par.	Red. tillage
Dry Wood Creek	3.79	2.80	3.74	2.40	5.60	15.85	2.23
Dry Wook Lake	3.34	2.62	2.78	1.78	5.21	14.76	2.39
County Ditch No. 22	3.25	2.25	3.43	2.20	4.45	12.61	2.59
Artichoke Creek	1.01	0.90	0.70	0.45	1.82	5.15	0.81
Efficiency	2.70	2.00	5.94	9.20	1.18	1.24	10.25

Fig. 7.3 BMPs' performance in reducing phosphorus load for Dry Wood Creek watershed basins



	Wascobs	Rip. buf.	Filter strips	Cons. crop rot.	Cons. cover par.	Red. tillage
Dry Wood Creek	4.46	4.64	3.37	10.47	20.07	2.94
Dry Wook Lake	4.78	5.33	3.87	10.41	19.99	4.27
County Ditch No. 22	4.40	3.85	2.80	10.90	20.94	3.53
Artichoke Creek	1.28	0.93	0.67	3.65	7.01	1.15
Efficiency	3.52	8.23	14.42	2.44	1.74	15.21

Fig. 7.4 BMPs' performance in reducing sediment load for Dry Wood Creek watershed basins

In the 2nd scenario, a different set of subbasins for BMP adoption were nominated (Fig. 5.11b) based on the farmers' CI criteria alone and resulted in efficiencies lower than the first scenario for all 3 BMP combinations.

7.4 Implications of HSPF-SAM based analysis

7.4.1 Intelligible watershed comprehension using SAM

Before developing an effective management strategy for a watershed, it is imperative to understand the affected areas and the sources contributing towards the impairment of the same. The Dry Wood Creek watershed was scrutinized using different modes (maps, plots, and tables) presenting the various statistical information concerning contamination in the study watershed.

Table 7.5 Optimization case scenarios with integrated BMPs

Case No.	BMPs integrated	Farmer participation level (%)	Reduction in Sediment (%)	Reduction in Phosphorus (%)	Budget (million $)
1	NMMI, CCP, CCR, and Wascob	97.5	86.3	73.1	7.58
2	NMMI, RB, FS, RT, and Wascob	100	49.2	44.5	1.48
3	NMMI, RB, FS, CCP, CCR, RT, and Wascob	50	65.1	52.5	4.1
4	NMMI, RB, FS, CCP, CCR, RT, and Wascob	83.7	83.4	73.1	6.85
5	NMMI, RB, FS, CCP, CCR, RT, and Wascob	83.7	80.6	71.1	5.1

Table 7.6 Integrated and optimized allocation BMPs to Dy Wood Creek watershed basins for 'case 5' for achieving phosphorus reduction

Cost effectiveness rank	Reduction by the BMP (%)	Progress to the target (%)	Cost ($)	Basin	BMP (Budget = 5.1 million USD)
1	2.33	2.33	10028	A210	Reduced Tillage (no-till)
2	2.321	4.561	13578	A210	Filter Strips, 50 ft wide (Cropland field edge)
3	1.612	6.263	13265	A220	Reduced Tillage (no-till)
4	0.889	7.152	7336	A230	Reduced Tillage (no-till)
5	3.324	10.476	32796	A210	Riparian Buffers, 100 ft wide (replacing row crops)
6	2.709	13.185	24591	A250	Reduced Tillage (no-till)
7	0.507	13.692	4760	A240	Reduced Tillage (no-till)
8	1.096	14.788	12424	A220	Filter Strips, 50 ft wide (Cropland field edge)
9	0.602	15.39	6871	A230	Filter Strips, 50 ft wide (Cropland field edge)
10	2.039	17.429	26329	A250	Filter Strips, 50 ft wide (Cropland field edge)
11	0.257	17.686	3307	A240	Filter Strips, 50 ft wide (Cropland field edge)
12	1.597	19.283	30009	A220	Riparian Buffers, 100 ft wide (replacing row crops)
13	0.876	20.159	16597	A230	Riparian Buffers, 100 ft wide (replacing row crops)
14	2.943	23.102	68785	A210	Water and Sediment Control Basin (Cropland)
15	2.869	25.971	63595	A250	Riparian Buffers, 100 ft wide (replacing row crops)
16	0.381	26.352	7987	A240	Riparian Buffers, 100 ft wide (replacing row crops)
17	1.897	28.249	66215	A210	Nutrient Management + Manure Incorporation
18	1.726	29.975	74702	A220	Water and Sediment Control Basin (Cropland)
19	0.945	30.92	41315	A230	Water and Sediment Control Basin (Cropland)
20	9.747	40.667	599196	A210	Conservation Cover Perennials
21	2.305	42.972	124489	A250	Water and Sediment Control Basin (Cropland)
22	0.514	43.486	24025	A240	Water and Sediment Control Basin (Cropland)

Cost effectiveness rank	% Reduction by the BMP	Progress to the target (%)	Cost ($)	Basin	BMP (Budget = 5.1 million USD)
23	1.633	45.119	222358	A210	Conservation Crop Rotation
24	0.651	45.77	41991	A230	Nutrient Management + Manure Incorporation
25	1.187	46.957	75923	A220	Nutrient Management + Manure Incorporation
26	1.366	48.323	111061	A250	Nutrient Management + Manure Incorporation
27	0.408	48.731	27642	A240	Nutrient Management + Manure Incorporation
28	0.111	48.842	6886	A260	Reduced Tillage (no-till)
29	0.227	49.069	14898	A270	Reduced Tillage (no-till)
30	6.07	55.139	687953	A220	Conservation Cover Perennials
31	3.3	58.439	380482	A230	Conservation Cover Perennials
32	1.003	59.442	254961	A220	Conservation Crop Rotation
33	0.529	59.971	141010	A230	Conservation Crop Rotation
34	6.904	66.875	1006338	A250	Conservation Cover Perennials
35	0.0561	66.931	4784	A260	Filter Strips, 50 ft wide (Cropland field edge)
36	2.126	69.057	254779	A240	Conservation Cover Perennials
37	1.096	70.153	372958	A250	Conservation Crop Rotation
38	0.115	70.268	10350	A270	Filter Strips, 50 ft wide (Cropland field edge)
39	0.353	70.621	94423	A240	Conservation Crop Rotation
40	0.0835	70.705	11555	A260	Riparian Buffers, 100 ft wide (replacing row crops)
41	0.17	70.875	25000	A270	Riparian Buffers, 100 ft wide (replacing row crops)
42	0.113	70.988	34756	A260	Water and Sediment Control Basin (Cropland)
43	0.146	71.134	47695	A270	Water and Sediment Control Basin (Cropland)
Total	71.134	71.134	$5,100,003		

The observed high phosphorus (96%, Table 7.2) and sediment load (90.8%, Table 7.3) from the croplands in Dry Wood Creek watershed could be because of the high use of fertilizers and pesticides and the current agricultural practices (Chen et al., 2019; Issaka et al., 2019). BMPs are deemed as the most effective for curbing the excess nutrient and sediment loads generated from agricultural fields (Opoku-Kwanowaa et al., 2020; Wang et al., 2019). Practices such as conservation crop rotation could additionally endow economic support and water conservation. The total accumulated phosphorus and sediment loads from different land uses cause increase in pollution loads in the rivers, lakes, and other waters of concern. However, there is a difference (reduction) in the total phosphorus load which is transferred from the Artichoke Creek watershed (Table 7.2) to its reach. This could be explained as 92% of the land is covered by the land uses mentioned in Tables 7.2 and 7.3, which means that the load generated from one land use (primarily croplands in this study) is transported across others (grasslands, forests, and pasture) as the water finds its way to the reach. Since the grasslands, forests, and pastures have very low pollution and serve as the surface water filters for nutrient removal (Schira, 2016; Izydorczyk et al., 2018), the water transported across them is treated. In contrast, Dry Wood Lake and Dry Wood Creek have more phosphorus load than the load generated by their basins' land uses. This could be true because the Dry Wood Lake River water gets its contribution from both Artichoke Lake and County Ditch No. 22 River, which contributes to the increased nutrients and sediment load (Ji, 2012). Likewise, the increased load in Dry Wood Creek could be answered. The variance in basin sediment loads the reach sediment load could be justified similarly.

7.4.2 Increasing scenario effectiveness through participation of stakeholders

A proper judgment on the performance of a particular BMP is subjected to the degree to which the site conditions could be replicated in a modeled design scenario. These subjective conditions involve criteria under broad categories like environment, economics, legal regulations, site characteristics – soil, terrain, and technical or scientific details regarding pollutants, BMP, and the waterbody (Revitt et al., 2003), which is quite a complicated in models such as HSPF. The scenario design in SAM considers these categories by including special factors such as farmer participation, reference suitability factor, and BMP efficiency and consequently delivers effective estimates of the BMP performance (Fig. 7.5).

The conservation cover perennials have excelled marginally for both nutrient and sediment reduction. This could be true because the perennials have wide applicability, i.e., these could be grown practically almost anywhere (Christianson et al., 2016), and secondly, they have a high nutrient reduction ability because of their high annual uptake of water and nutrients as compared to fellow row crops like corn and soybean. Perennial crops consume water and nutrients for much longer duration until the soil freezes in the winter and begins its uptake earlier in the spring compared to row crops. Randall et al. (1997) and Laura Christianson et al. (2016) advocated 96% less nutrient loss when a continuous corn system is replaced by unfertilized alfalfa over a year. Though this practice renders high load reduction and applicability, however, the maximum implementation cost amongst all other practices minimizes its overall efficiency (Kenner et al., 2017). Whereas, the reduced tillage (no-till) entails minimum soil disturbance, and that too only during planting and fertilizers application. The no-tillage practice is found to be effective for soil and water conservation (Busari et al., 2015) and high nutrient (Zhang et al., 2020) and sediment (Yuan et al., 2008) reduction capacity have been reported by the past studies.

Similarly, high load reduction capacities have been proclaimed for the filter strips by the researchers (Baumhardt and Blanco-Canqui, 2014). Filter strips treat water by intercepting the run-off and reducing the sediment and sediment-bound nutrients transport. Despite of having high pollutant load removal capacities, the lower total reduction exhibited by the filter strips could be attributed to their low reference suitability. The forehand inclusion of these practices into the PdT TMDL implementation plan (Water Resources Center - MSU, 2014) substantiates their better performance as well as the occurrence of less land needed to implement these practices. Conservation cover perennials, conservation crop rotation, nutrient management, and WASCOB BMPs have shown similar basin-wise trend for total phosphorus reduction (Fig. 7.3) i.e., with increase in percent area for high till crop land (from Dry wood creed (75.1%) to Dry wood lake (86.3%) to County ditch no. 22 (97%)), the percent phosphorus reduction decreased as well (Table 7.2 and Fig. 7.3). As each individual BMP has an implicit maximum nutrient holding/removal capacity. The increase in nutrient load beyond that limit reduces the overall percent reduction capacity of the BMP (Qiu et al., 2020). While Artichoke Lake shows minimum phosphorus percent reduction even for the lowest high till cropland area percent (58.6%). This could be true because Artichoke Lake has a minimum overall cropland percentage (around 70% while others have > 80%, Table 7.2) which naturally designates more land to other high land uses (developed and wetlands in this case) which were not treated by the BMPs.

7.4.3 Basin-wise optimized targeting of conservation practices

The results (Figs. 7.3 and 7.4) highlighted that no single BMP could attain the target percent reduction for total phosphorus (73.1%) and sediment (58.7%) as outlined by the PdT watershed

TMDL. In addition, each BMP has some inherent strengths and weaknesses (Jain and Singh, 2019), which makes it challenging to satisfy all the necessary requirements to be fulfilled by a single practice. Thus, a combination of the BMPs is recommended through which the contemporary practices could offset each other's limitations (Xia et al., 2020). Further, through exercising cases 3 and 4, it has been observed that even with the integrated application of practices, the required results could not be achieved until and unless there is a minimum 83.7% farmer participation. Such high farmer participation has earlier been gained in US in the past, e.g., a 93% farmer participation has been reported by Watershed Agricultural Council (James, 2005) in the Cannonsville Watershed. The farmer survey for understanding the barriers which could hinder the conservation practice adoption and consequent farmer awareness, training, and support programs, and apropos incentivization could be useful for gaining high farmer participation (Sharpley et al., 2009; Kast et al., 2021). The last 7 ranks of cases 4 and 5 imply that to attain the last 2% reduction, it requires one to pay 34% more than the otherwise required cost, which has also been confirmed by the past research (Simpson and Weammert, 2007).

Over and above, it is a great challenge to search out for cost-effective alternatives, as there are always numerous factors involved simultaneously like: as reduction amounts by BMPs, effectiveness, and feasibility which in turn depends upon several political, socio-economic, physical, and ecological constraints (Kaufman et al., 2021; Zhang and Chui, 2018). Thus, an optimization algorithm is required to support the identification of cost-effective alternatives and improve the probability of achieving watershed pollution reductions goals from selected practices. This challenge, however, has been taken on by the SAM by including an optimization engine at its final stage, which enlists a least-cost-wise ranking of the targeted alternatives to basins. That not only supports complete target reduction achievement but also allows choosing a fragmental path to achieve cost-effective fractional reductions.

7.4.4 Applicability of HSPF-SAM based analysis in Indian context

The application of HSPF-SAM is pivoted at utilizing the HSPF model application files or the calibrated parameters for the study watershed and linking them with the basin shapefiles and consequent development of SAM project files using the PATH (Processing Application Translator for HSPF) application. The HSPF models are currently available and being developed for Minnesota state (USA) by MPCA. Such HSPF models could be effectively developed for the

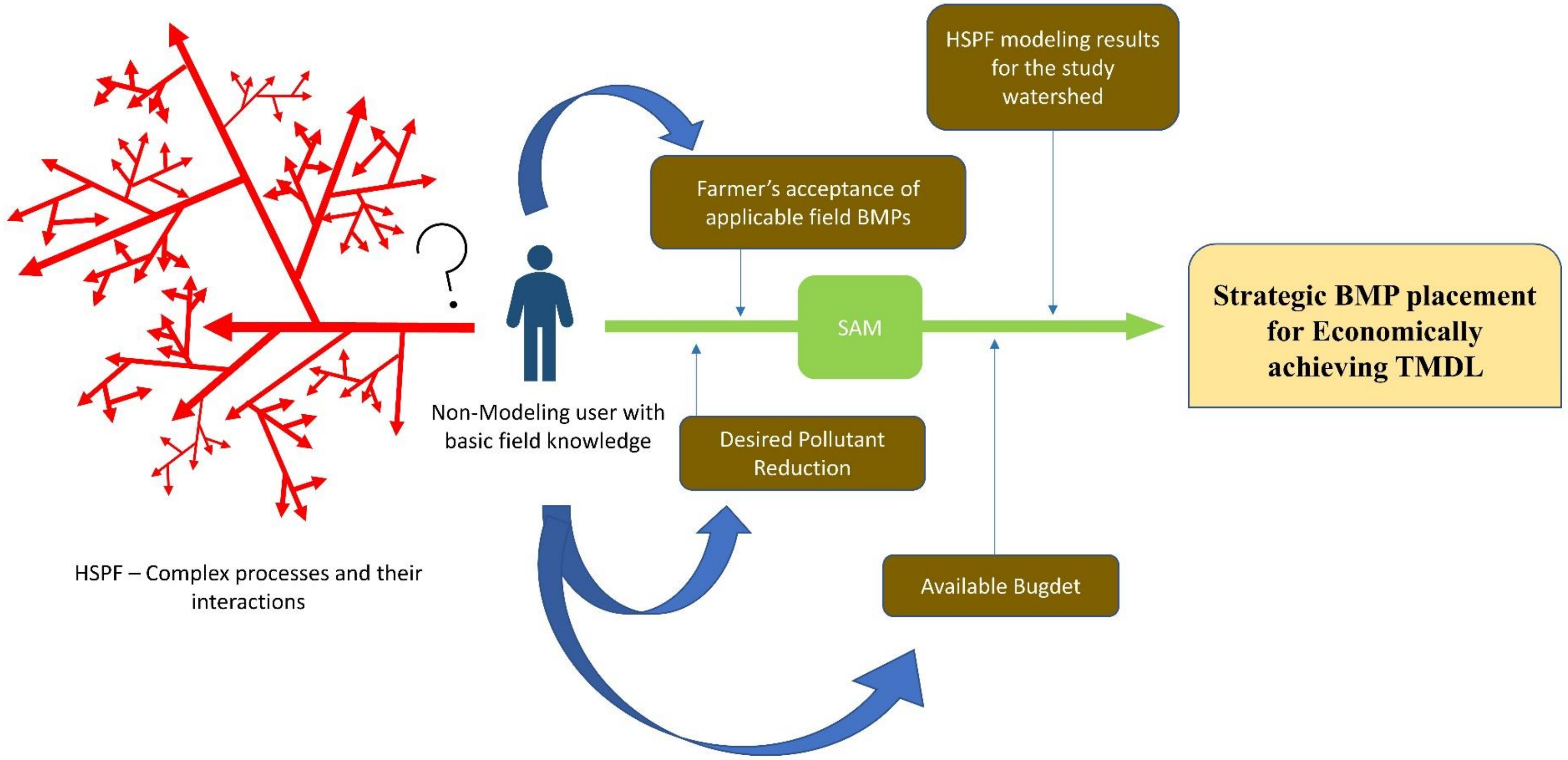


Fig. 7.5 Economic TMDL achievement avoiding complex modeling requirements.

Indian watersheds by utilizing the datasets encompassing watershed boundaries, meteorological, hydrologic, land use characteristics, etc., which have already been curated and employed for Muzaffarnagar (a district in Uttar Pradesh, India) in the 3rd chapter. However, there is a need to create a BMP dataset that includes the specific set of BMPs applicable in India. For example, the tile-line bioreactors (an effective BMP type practiced in the USA) necessitate or work in conjunction with the tile drainage systems whose absence in Indian agricultural systems prevents their pertinency in the Indian context. Additionally, there are variances in the BMPs implementation costs, processing cost, efficiencies, acceptability, etc., about varying vegetative patterns, soil conditions, agricultural field characteristics – size, shape, slope, agricultural practices, policies, and incentivization, etc. compared to the USA. Further, the sub-watershed polygon shapefiles of Muzaffarnagar could be linked to the HSPF parameters output files calibrated at the catchment outlet, followed by the linking of constituent source definition and creation of SAM files using the PATH application. Thus, the efficacy of HSPF-SAM based analysis for suggesting optimized, cost-effective, and efficient conservation practices for achieving TMDL could be imported or utilized for the Indian watersheds, provided the availability of the necessary databases.

7.4 Summary

Hydrologic Simulation Program Fortran (HSPF) has been a well calibrated, robust and trusted model for simulating the complex interactions of physio-chemical processes over different spatio-temporal scales. However, complex modeling pedagogy requirement and limitations of HSPF, such as intense coding necessity for evaluating the efficacy conservation practices, inability to incorporate farmers and decision maker’s opinion into the model, lack of flexibility to quickly develop economical TMDL scenarios, makes it challenging for practitioners to use and interpret HSPF model. Considering this, present study examines the efficacy of HSPF-based decision-support tool, Scenario Application Manager (SAM), which utilizes HSPF’s results to develop optimized management scenarios for economically achieving desired TMDL goals. Pomme de Terre watershed located in Minnesota, USA has been considered as study area and is divided into four sub-watersheds viz., Artichoke Creek, County Ditch No 22, Dry Wood Lake, and Dry Wood Creek to assess the effect of seven CPs (riparian buffers, conservation crop rotation, reduced tillage, etc) on TMDL planning. Overall, the study deals with two important aspects, viz. (i) developing HSPF-SAM, design scenarios and optimizing CP allocation to achieve TMDL reductions corresponding to sediment and phosphorus contaminants, and (ii) producing a basin-wide cost-effective strategic BMP implementation rank list while

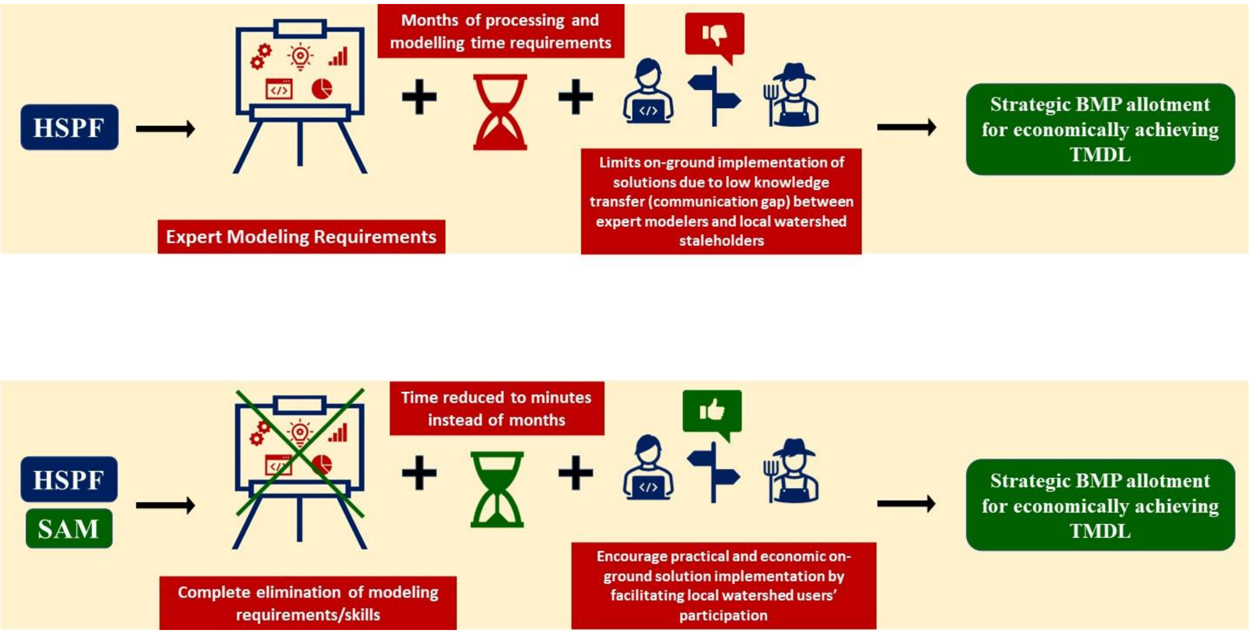


Fig. 7.6 Specific advantages of HSPF-SAM over HSPF.

incorporating farmer's opinion to guide the practitioners towards implementing BMPs in an economical way. Results indicate that reduced tillage and filter strips were found to be the two most efficient practices for pollution reduction; however, owing to their low reference suitability, the conservation cover perennials shared maximum load reduction. Results also revealed that no combination of CPs is eligible to achieve the TMDL unless there is a minimum of 83.7% participation of farmers toward CP implementation.

Consequently, while overcoming the limitations of HSPF requiring in-depth understanding of (i) model input parameters concerning land use, soil etc., (ii) principles governing the performance of various conservation practices, and (iii) modelling and programming skills, SAM, widens the applicability of modeling results by promoting field-scale conservation planning through enhanced involvement of amateur-modeling stakeholders directly connected to fields. Though

SAM offers many advantages over conventional HSPF model, but it still necessitates considerable quantitative watershed information which could limit its application. Hence, in the next chapter a fuzzy-based framework has been developed that executes the purpose similar to this chapter but in the absence of availability of the sufficient or even zero quantitative information, programming, modelling requirements, etc.

CHAPTER 8

NITRATE-NITROGEN MANAGEMENT USING PERENNIAL PLANT OPTIONS UNDER UNCERTAINTY

8.1 Introduction

Many Midwestern US states have adopted conservation practices to reduce nutrient transfer from agricultural fields (Brown et al., 2021; Stollenwerk et al., 2014). The efficient selection and field scale implementation of such practices require a systematic and considerate approach. A critical challenge toward the development of such a systematic decision-making approach is that these nitrate management practices are relatively novel. Therefore, not many knowledgebase/ research records are available which can quantitatively showcase the performance of these approaches over time (Christianson et al., 2016). Thus, in this chapter, the vitality of the fuzzy inference system has been adjoined that could model and target the conservation practices even when there is uncertainty in the experts' opinion and the data/information available is qualitative. This chapter in-depth studies and learns from the various land-use changes and contexts in the Des Moines lobe till watershed (Mississippi River basin) which have led to extensive Nitrate-nitrogen (NO_3-N) discharge; discusses applicability of innovative perennial approach in integration with the practices discussed in the previous chapter; and finally allocates these options using the fuzzy based approach.

Nitrate-nitrogen (NO_3-N) discharge significantly affects the coastal ecosystems of the Gulf of Mexico (Rabalais and Turner, 2019). The effects include reduced dissolved oxygen and light penetration resulting in harmful algal blooms and loss of aquatic habitat. After the 1993 floods, the area-coverage of hypoxic waters in the Gulf of Mexico has enlarged from 8000 km^2 in the 1980s to over 20,000 km^2 (Bianchi et al., 2010; Rabalais and Turner, 2019). The size of the zone was slightly smaller, ~ 18,000 km^2 in 2019, but was greatly reduced in 2020 due to hurricane activity in the Gulf of Mexico. The annual NO_3-N concentration in the Mississippi River has more than doubled since the 1960s as compared to the first half of the twentieth century (Cao et al., 2018; Turner and Rabalais, 1991). Employing an ensemble of four hypoxic models (Scavia et al., 2017) indicated that a 59% nitrogen load reduction in Mississippi River can achieve hypoxic zone reduction to 5000 km^2 (Fig. 8.1a). Alexander et al. (2000) studied NO_3-N movement in the upper mid-western tributaries of the Mississippi River and recommended actions to stabilize its transport to the Gulf of Mexico. David et al. (2010) conducted a study to identify the major source areas for N inputs in Mississippi river using a non-linear model and found that the highest nitrate N inputs corresponded to Southwest Minnesota states' (Iowa, Ohio, Indiana, Illinois) tile-drained corn belt. Particularly during spring (April–June), the volumetric nitrogen load discharge has increased due to changes in agricultural practices such as the application of nitrogen fertilizer (Goolsby et al., 1999). Although the cropland production has remained stable over the last half-century (Ribaudo et al., 2011; Terry and Kirby, 1998; Yearbook, 2002), the annual nitrogen use in the USA now exceeds ten million metric tons. During this period, tile drainage has significantly altered the hydrologic pathways (Magner and Alexander, 2002; Rallapalli et al., 2022; Srinivas et al., 2022) in the agricultural watersheds of the upper midwestern USA, resulting in excessive nutrient delivery to surface waters (Alexander et al., 2000; Smith et al., 2015). Van Meter et al. (2018) suggested that a long-term commitment and a large-scale change in agricultural practices would be necessary to meet the Watershed Nutrient Task Force's current goals for lowering the Gulf hypoxic zone. States in the US's Midwest have implemented conservation measures to lessen nitrogen runoff from agricultural areas.

However, to address the absence of the adequate knowledge base and quantitative information of these strategies over time, a fuzzy inference system has been used to model and target conservation practices. The fuzzy sets frameworks are the efficient ways for modeling scenarios involving subjectivities and diverse perceptions of different stakeholders, uncertain field data, and conflicting linguistic responses of the decisions makers (Liu et al., 2021; Pan et al., 2018; Sajith et al., 2022; Singh et al., 2007; Srinivas et al., 2017; Xu and Qin, 2015). Fuzzy logic methods are suitable in handling such uncertainties by employing suitable membership functions and aggregating them under different fuzzy environments like Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Analytical Hierarchy Process (AHP), etc. (Pan et al., 2018; Srinivas and Singh, 2018). Further, fuzzy techniques are also helpful in integrating the linguistic responses with the quantitative datasets available for nitrate management practices (Razavi- Toosi and Samani, 2019; Srinivas et al., 2015, 2020). The poorly drained soils of north-central Iowa and south-central Minnesota, modified by sub-surface drainage, are the primary sources of the high nutrient loads to the Mississippi River. This region, underlain by a dense, blue grey glacial sediment, is known as the Des Moines lobe till (DMLT) (Fig. 8.1b). The last glacial advance of the Des Moines lobe created a dense blue grey till that is relatively impervious to downward percolation and recharge to underlying aquifers. The scraping of sandstone, limestone, and shale by the multitude of glacial passes over the landscape has produced calcareous clay rich material. The upper regions of this material then weathered over time to form well-to-poorly drained olive-brown loam and clay loam soils. The presence of prairie and wetland vegetation further added organic matter through root turnover and root exudates to create deep dark productive soils that are now considered some of the most productive agricultural soil in the world (Hansen et al., 2018).

Over the past century, land use in this region has changed from an internally drained prairie-wetland complex to an intensively managed corn-soybean production system (Fig. 8.2) that not only provides food but also ethanol energy. However, drainage was necessary to make these soils productive for row crops because of the dense underlying till. Prairie lakes and wetlands were the earliest drained portions of the landscape (Magner et al. 1993), but modern technology has also allowed subsurface tile-drains to be placed economically throughout southern Minnesota and northern Iowa. Presently, subsurface, or shallow ground water drainage leaches NO_3-N from the soil profile (Husk et al. 2017; Randall et al. 1997) and transports not only nitrogen but also, another commonly limited macronutrient that leads to eutrophication, dissolved phosphorus, into surface waters. Thus, the primary objective of this chapter is to address the water-quality degradation from land-use changes in the DMLT by offering decision support concerning strategic placement of recommended perennial plant options using fuzzy logic-based expert systems.

8.2 Methodology

The present section discusses four perennial management options to be targeted at different landscape positions bearing low row-crop yields for addressing the problems concerning water quality degradation in the upper Mississippi River basin and hypoxia in Gulf of Mexico. The

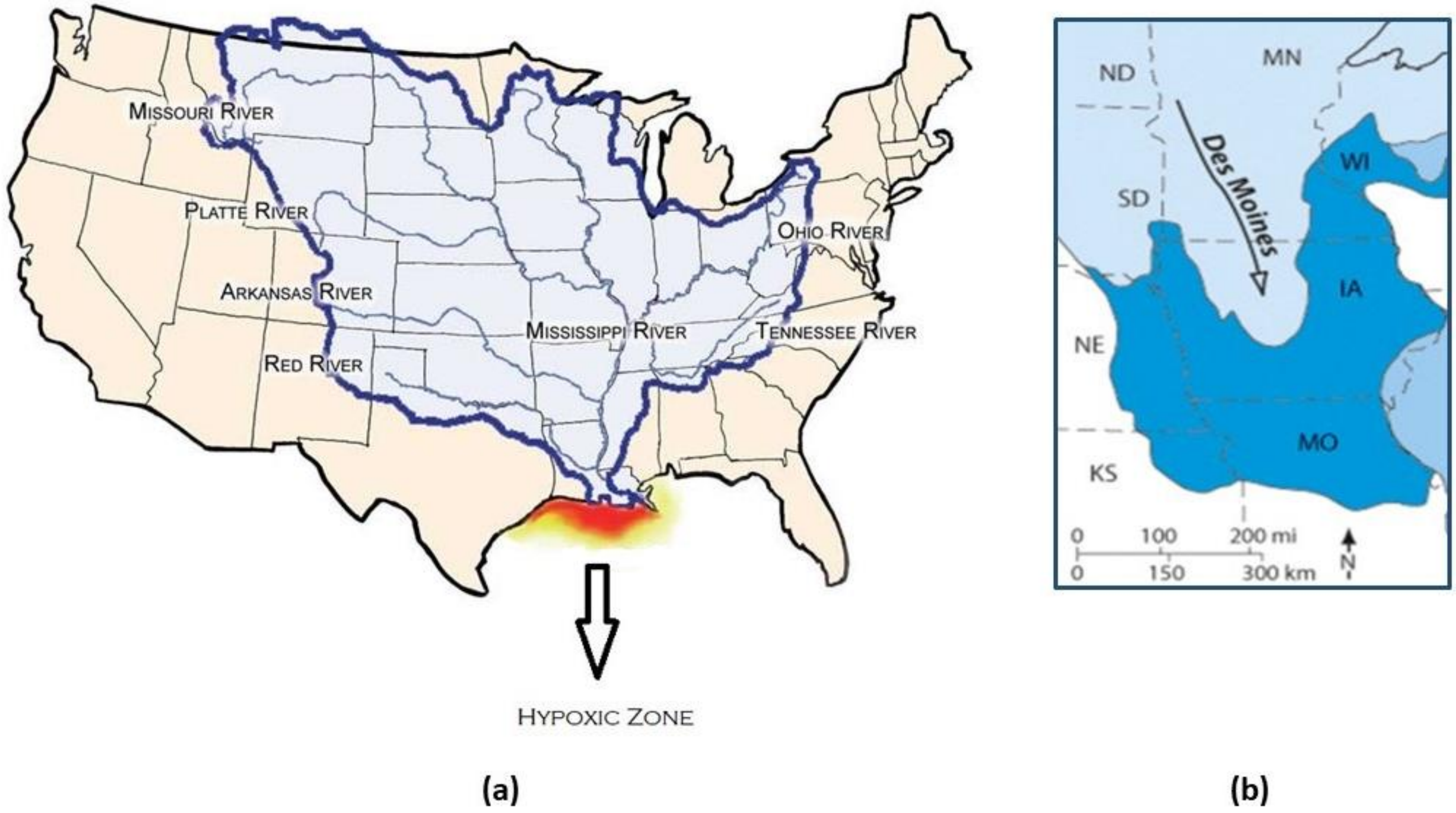


Fig. 8.1 (a) Location of the Hypoxic Zone and the Mississippi River Basin. (b) The extent of glacial advance of Des Moines lobe till in upper Midwest.

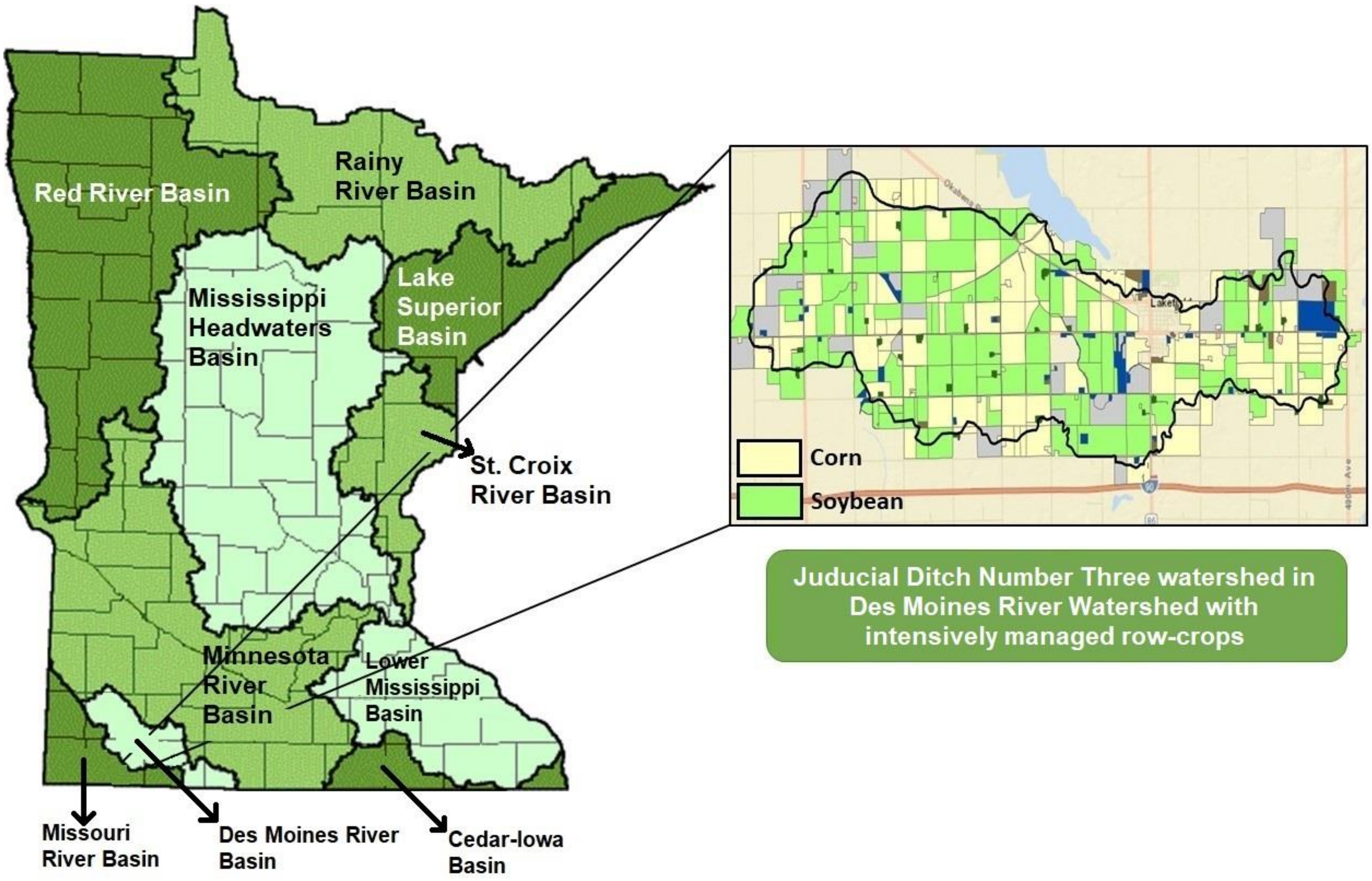


Fig. 8.2 Minnesota river basin and specific area of Des Moines River Basin.

non-point pollution from agricultural watersheds and the near-channel sources are two primary sources of water quality impairment (Belmont et al., 2011; Dalzell et al., 2004). Thus, the upland options, including swales, wetlands, and field edges and the riparian corridors, including ditches and natural streams are the potential locations selected for implementation of perennial vegetation options. Lastly, the strategic field scale deployment of these management options and the associated uncertainty is handled using the fuzzy inference system approach.

8.2.1 Depression wetland storage

The uplands in the DMLT are typically planted with annual row crops such as corn and soybeans. However, some landscapes contain depressions or swales which hold or allow the flow of water after snowmelt, soil thaw, and storm events. If water remains in the soil for more than 48 h, annual crops such as corn suffer physiological stress and stunted growth, which means lower crop yield and reduced farm profit (Zhao et al., 2016). The lowering of the water table for accommodating crop growth poses a challenge to the restoration of upland wetlands (Menzel, 1983). However, a lower water table indicates that the channel bed elevation could be lower with much reduced roughness (Manning’s *n*) to allow gravity flow of lateral drainage systems. The collective effects of drainage have resulted in channel instability, streambank erosion, and impaired water quality in south-central Minnesota (Magner et al., 2004; Pierce, 2020). Annual streamflow volumes and peak flows associated with frequently occurring events (1.5 and 2.0-year recurrence intervals) have been shown to increase dramatically because of these cumulative effects. Some landowners have decided that a pattern drain-tile with a surface intake riser can move excessive water from the swale quickly enough to prevent crop damage. However, this practice is not environmentally sustainable since water, nutrients, and sediment are quickly transported off-site resulting in downstream water quality impacts (McLellan et al., 2018). The cost associated with pattern drain-tile is higher than other conventional subsurface drainage systems.

Further, a pattern drain-tile system may fail if the watershed drainage network becomes overloaded from too many landowners draining their individual fields (Magner, 2011). The wettest year on record for Minnesota occurred in 2019 in over 100 years of data collection (MN

State Climatology Office). Row-crop producers are keen to eliminate the cultivation on marginal land that yields a net negative return on investment (Muth, 2014); for some, getting a government payment to take land out of production makes financial sense. Perennial plant systems such as willows (*Salix* spp.) fit both federal and state conservation programs and provide an alternative to flooded row crops (Jager et al., 2020). These plants tolerate wet conditions such as upland DMLT swales and can be planted using cuttings. While willows typically do not fit in a corn soybean system, they could easily do so with the right incentives to promote fish habitat. There may also be some limited demand for biobased products such as levulinic acid or ornamental varieties such as diamond and purple osier that could be grown and sold in specific markets (Chen, 2015). Also, there are some other upland areas of the DMLT which are extremely flat and cannot be drained adequately to support annual row crops like the Watonwan River watershed. The drainage occurs in their headwaters and the lower reaches, but not in the flat middle portion. However, if the county tilemain is broken in the flat mid-section of the watershed, water will flow overland and then develop into a wetland from the headwater drainage over time (Crumpton, 2001). The developed wetland can be used for treating the high NO_3-N water exported from the headwater portion of the watershed by harvesting biofuel, cattails, animal bedding, or fibre; the landowner would benefit minus costs (Alsadi, 2019).

8.2.2 Two-stage Ditch System

In a ditch system, flood flows are contained vertically by the trapezoidal design of the ditch, offering little attenuation to both floods and nutrients. Natural streams that have accessible floodplains and terraces provide lateral flood water conveyance. High NO_3-N in subsurface water from drain-tiles before it enters a ditch, as in an incised channel or gully, (Lien and Magner 2017) provides an opportunity to denitrify water. However, not all soil map units in the DMLT are excessively flat lakebeds that allow for wetland creation. In some DMLT landscapes, ditches and incised streams are the only feature containing water; therefore, creative ways to modify the ditch geometry, such as a two-stage design, could help treat high NO_3-N water (Kramer et al. 2019). The previously discussed perennial plant options may not be acceptable to landowners.

However, if the drainage authority can be convinced to employ the use of a two-stage ditch design based on potential maintenance cost savings, a value-added benefit could also be NO_3-N denitrification via vegetative floodplain bench (Kramer et. al. 2019). A two-stage ditch design (Christner et al. 2004; Kramer et al. 2019) provides a small floodplain inside of the ditch geometry for vegetative growth and frequent flood interaction with biological material. Currently, woody vegetation is not acceptable to landowners who require ditches for adequate drainage. Therefore, a native grass such as prairie cordgrass (*Spartina pectinata*) could be grown on the floodplain bench of the ditch (Krider et al. 2017). This grass offers improved economic viability compared to the current ditch vegetative species. Prairie cordgrass has the capacity to be used as a biofuel or as a fiber for paper production. Without the two-stage ditch design, high NO_3-N in tile-drains will move unimpeded through ditches into progressively larger streams and rivers. The two-stage ditch with prairie cordgrass offers an environmentally and potentially economically sustainable solution to the NO_3-N leaky DMLT landscapes.

8.2.3 Riparian systems and Saturated buffers

The critical role of stable stream-riparian systems in controlling pollutants discharged from agricultural watersheds was recognized two decades ago (Karr and Schlosser, 1978; Lowrance, 1982; Schlosser and Karr, 1981). In non-subsurface drained agricultural settings, riparian buffers effectively reduce nutrient transport to surface waters (Lind et al., 2019). Lowrance et al. (1982, 2002) explored the relationship between riparian buffers and the resultant nutrient assimilation. Groundwater was once considered an important pathway of nutrient transport. However, Lowrance (2002) and other research (Groffman et al., 1992; Haycock and Pinay, 1993; Jordan et al., 1993; Robinson, 2015; Yu et al., 2018) confirmed that the agricultural sources of NO_3-N are substantially reduced in stream-riparian systems given adequate contact time with organic-rich soil containing denitrifying bacteria. Osborne and Kovacic (1993) further studied vegetated buffer strips and observed that row-crop tile-drained fields short-circuited riparian buffers by directly establishing a connection of precipitation through tile-drains to ditches and streams. They proposed a wetland interception design that Schultz et al. (1995) employed, who noted a 5-fold NO_3-N reduction with limited cattail (*Typha sp*.) production and hydraulic residence within the DMLT. This result was reconfirmed by Donovan (2012) in southwestern Minnesota.

A more recent approach is the use of saturated buffers (Jaynes and Isenhart, 2014). This approach adds tile-drains at the edge of a field, running parallel to the stream, to prevent a direct discharge into the stream (Tomer et al., 2020). A portion of the sub-surface water is routed into the riparian soil and allowed to move advectively through the sediment and ultimately diffusely discharge into the stream (Lien and Magner, 2017). The existing vegetation in riparian soils can uptake both nutrients and water. Additionally, other perennials such as cottonwood (*Poplus* spp.) or hazelnut (*Corylus* spp.) could be grown around the outer edge of the field. Harvested cottonwood could turn into woodchips for the construction of denitrifying bioreactors, whereas the hazelnut could produce confectionary nuts, soaps, biodiesel, and lubricants.

Once dominated by perennial prairies, savannahs, wetlands, and riparian forests, the landscape of the DMLT has undergone major changes as annual cropping systems came to dominate the landscape, particularly since 2000 (Arenas Amado et al., 2017; Lien and Magner, 2017). The loss of perennial vegetation in southern Minnesota during the 20th century happened over decades. Several researchers have investigated the cumulative effects of these land use changes (Arenas Amado et al., 2017; Goolsby et al., 1999; Lien and Magner, 2017; Magner et al., 2004) on the water resources of the Mississippi River and the Gulf of Mexico. Along with a decline in water quality, several cumulative effects such as increased runoff, soil erosion, and nutrient export have been observed (Leach and Magner, 1992; Zhang, 2019). Perennial crops, on the other hand, would exhibit lower runoff than annual crops (Randall et al., 1997) to provide some degree of soil protection during these months.

Based on the above discussion, it can be inferred that strategic perennial management options could help in addressing the problems concerning hypoxia in Gulf of Mexico. Strategic planning involving multi-criteria decision making and fuzzy logic- based expert systems can be used to assess the degree of suitability of various strategies (Singh et al., 2007; Srinivas et al., 2017). Additionally, fuzzy logic proposes a framework to simultaneously handle uncertainties concerning external criteria as well as the decision maker's preferences (Pan et al., 2018). Srinivas et al. (2020) used fuzzy logic to incorporate the opinions of farmers and local watershed users in planning the best management practices such as nutrient removal wetlands, bioreactors, riparian buffers, etc. in the Plum creek watershed of Minnesota.

8.2.4 Fuzzy based expert system for uncertainty analysis

The strategic options discussed in the previous sections can be broadly categorized into four categories viz. (1) Depression wetland storage, (2) Saturated buffers, (3) Two stage ditches, and (4) Riparian buffers. Each strategic option is further characterized using four parameters, these are Cost Effectiveness (CE), Nitrate Reduction Potential (NRP), Water Quality Improvement (WQI), and Level of Acceptance (LOA). CE is the total cost required by a given strategic option to remove 1 pound of nitrate from agricultural drainage water and NRP is the percent reduction in nitrate content after agricultural water drained through a particular management practice. WQI and LOA are the two qualitative parameters each of which is defined by four classes. In WQI, these four classes are the different permutations of biofiltration, denitrification, and flow reduction. While the WQI in saturated buffers treats tiled drainage water in addition to land surface water treatment in the riparian buffers. The classes in LOA are the perceptions of local watershed landowners, farmers, and landowners toward implementation of a particular strategic option.

Broadly these classes or perceptions are related to the intricacy involved in management and acceptance of a practice and the consideration of incentivization. Table 8.1 provides the most probable values or the average values for CE and NRP parameters and the qualitative classes corresponding to WQI and LOA parameters for each strategic option. The four parameters (i.e., CE), characterizing the main problem statement, have innate uncertainties. For instance, saturated buffers and two-stage ditches are the relatively two novel strategic options, thus, the parameters related to these approaches lack exhaustive understanding (Christianson et al., 2016). Hence, inherently associated with a quantum of subjectivity and uncertainty. MATLAB-based fuzzy expert systems could help to develop a flexible decision support system that mathematically estimates the final degree of suitability of a strategy. Authors have given detailed explanations of the methodology in the past (Srinivas et al., 2015, 2017). This method consists of four key steps (a) fuzzification of input criteria using appropriate membership functions; (b) expert rule evaluation (inference); (c) aggregation of the rule outputs (composition); and (d) defuzzification to obtain crisp scores. In first step, the criteria values are first normalized and then linguistically expressed via classes such as ‘Very High (VH)’, ‘High (H)’, ‘Moderately High (MH)’, and ‘Moderate (M)’ using the membership functions. Secondly, under the experts’

Table 8.1 Strategic options and corresponding criteria considered for the study

Criteria→ Strategic option↓	Cost Effectiveness (CE) ($/lb N)	Nitrate Reduction Potential (NRP) (%)	Water Quality Improvement (WQI)	Level of Acceptance (LOA)
Depression Storage (DS)	3.36	33.7	Runoff reduction and sediment pollution removal (RRSP)	Commonly perceived as nuisance and hard to maintain (CNHM)
Saturated Buffers (SB)	1.22	32	Flow reduction and Nitrogen removal (FRNR)	Requires little maintenance and low initial cost (deals with both surface and subsurface pollutants) (LMLI)
Two-stage ditch (TSD)	2.1	12	Denitrification and Biofiltration (DNB)	Has gained support from farmers, drainage managers, water conservation professionals (SFMC)

Criteria→ **Strategic option↓**	**Cost Effectiveness (CE)** **($/lb N)**	**Nitrate Reduction Potential** **(NRP) (%)**	**Water Quality Improvement** **(WQI)**	**Level of Acceptance** **(LOA)**
Riparian buffers (RB)	2.98	4.32	Slowdown of runoff and Nitrogen Removal (SRNR)	Acceptance with conflicts, incentives may be required (ACI)

Sources: *(Deletic and Fletcher, 2006; Kult and Klein, 2018; Christianson et al., 2016; Weiss et al., 2005; Roley et al., 2016; Sabater et al., 2003; Smith et al., 2013)*

guidance fuzzy inference rules are formed. These rules are comprised of IF-THEN statements aggregated using fuzzy operators (AND or OR). There can be a total of n number of rules, where,

$$n = (no. of\ linguistic\ variables)^{(no.of\ parameters)} \tag{8.1}$$

For example, considering 4 input parameters (i.e., cost effectiveness), each of which is expressed via 4 linguistic variables (i.e., Very High, High). So, total possible rules can be

$$n = (4)^{(4)} = 256 \tag{8.2}$$

In the next step, numerous rules are fired using the input parameters and an integrated membership function is obtained by integration of the rule outputs. Lastly, the crisp score (Z) is obtained by defuzzification of the integrated membership function. There are several defuzzification methods available, the present study centroid method is used to compute the crisp score for estimating the degree of suitability of strategic options under discussion.

$$Z = \frac{\int \mu(z).z\,dz}{\int \mu(z)\,dz}\text{; where z} \in \text{C and C is a fuzzy set} \tag{8.3}$$

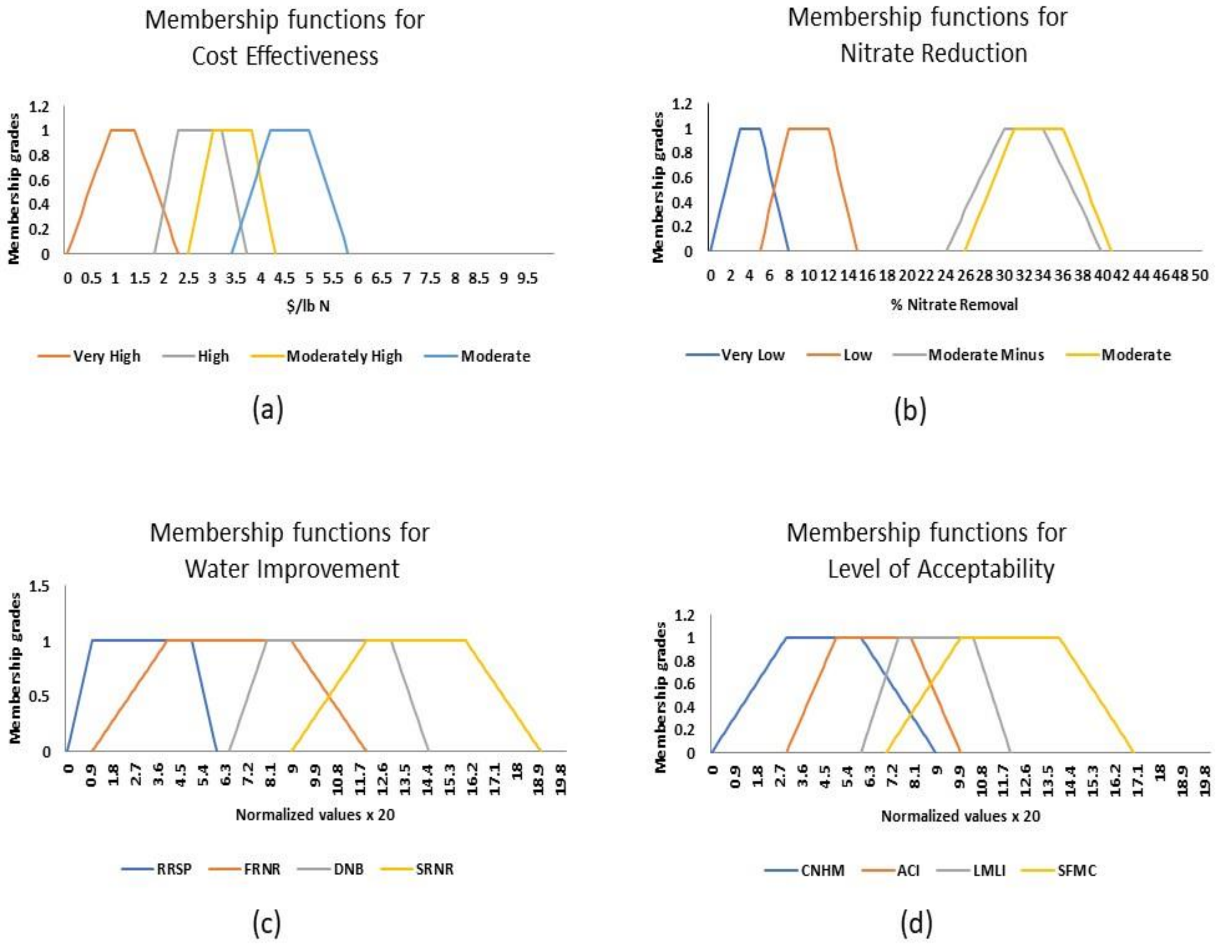
8.3 Results and Discussion

8.3.1 Fuzzification using membership functions

The membership functions for CE and NRP criteria are normalized on the scale of 10 $/lb N and 50% respectively while the membership functions for the qualitative criteria are designed based on the relationship among the different members and the expert opinion. The shape of the representative membership function is subjected to the nature or the distribution of selected criteria (Srinivas et al., 2017). The criteria corresponding to this analysis observe a common pattern i.e., each category parallel to a given criterion follows a steady rise and drop sandwiched by a range of normalized values linking to maximum membership grade. For instance, the range of values for the input criteria ‘CE’ is classified into four classes ranging from ‘Very High (VH)’ to ‘Moderate (M)’ (Fig. 8.3a) based on the most probable values of CE as listed in Table 8.1. The ‘very high’ cost effectiveness category (red coloured MF in Fig. 8.3a) corresponding to saturated buffer option, follows a steady rise until 0.09 normalized value and then observes a range of values from 0.09 to 0.14 corresponding to maximum membership grade followed by a steady downfall culminating at 0.23 normalized value. Similarly, NRP is calibrated on a scale from ‘Very Low (VL)’ to ‘Moderate (M)’. WQI and LOA are also categorized accordingly (Fig. 8.3). The combined effect of these inputs (Fig. 8.4) for any given strategy results in an output which assists the decision maker in selecting suitable best management practice from the quartet of suggested options.

8.3.2 Fuzzy expert rule evaluation

‘IF-THEN’ rules are subsequently deployed to additively synthesise the outputs of the four input criteria (Fig. 8.4 and Fig. 8.5). An expert panel consisting of fifteen stakeholders (i.e. Academicians & Researchers - 6, Watershed planners - 4 , and local farmers - 5) from the upper Mississipi watershed was consulted and a survey questionnaire was circulated among them (Appendix-B). The questionnaire recorded expert’s jugdements towards the selection of different strategic options under different possible scenarios.



(a) (b) (c) (d)

Fig. 8.3 Membership functions of the criteria used for developing fuzzy decision support viz. a.) Cost effectiveness, b.) Nitrate reduction potential, c.) Water quality improvement, and d.) Level of acceptance criteria

For illustration, the rule 1 can be written in the following form:

Rule 1: IF 'cost effectiveness' is moderately high, AND 'nutrient reduction potential' is medium, AND 'water quality improvement' required is runoff reduction and sediment pollution removal, THEN the choice of BMP is 'Depression Storage'

These set of rules are coherent with the past research. As, Kult and Klein (2018) assessed the effectiveness of seven satured buffers in Iowa, Illinois, and Minnesota, the saturated buffers were realized as the cost-effective options while supporting high nitrate reduction from tile drained waters. Also, Christianson et al. (2016) mentions that saturated buffers improve the

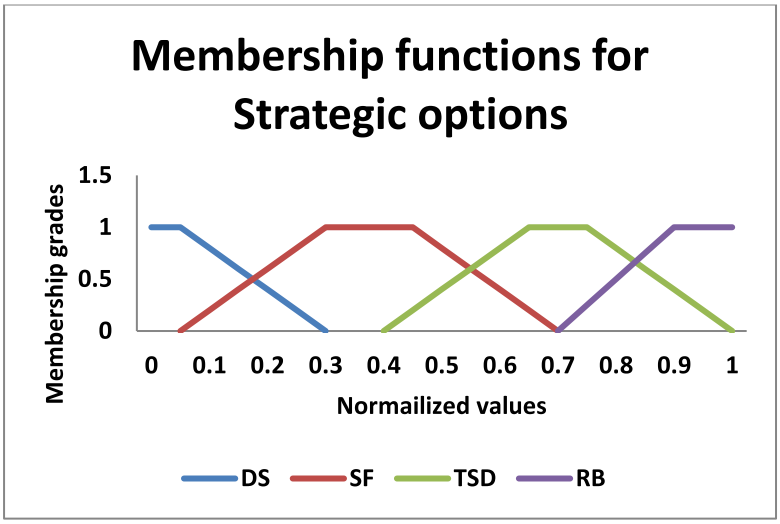


Fig. 8.4 Membership functions for output i.e. choice of best management practice

quality of water by slowing down the run-off from fields and require low intial investment and very little maintenance. Thus, the rule numbers 2, 6, and 7 (Table 8.2) can be explained. Similary, a sum total of twenty input-output rules can be explained. The most dominant responses from the collective set of responses were chosen as the survey outcome. Thus, the survey resulted in development of 20 rules that comprehensively captured and consolidated the on-ground preformance and general perceptions related to the different strategic options.First 7 rules out of 20 are listed in Table 8.2 for brevity. A filled out example of the survey output/rules can be accessed through the supplementary material (Appendix-B, Questionnaire B2).

Table 8.2 Fuzzy expert rules developed for the study

Rules↓	**Inputs**				**Output**
Operator →	**IF**	**AND**	**AND**	**AND**	**Strategic option**
Criteria →	**Cost Effectiveness**	**Nitrogen Reduction Potential**	**Water Quality Improvement**	**Level of Acceptance**	
Rule 1	Moderately High	Moderate	RRSP	CNHM	Depression storage
Rule 2	Very High	Moderate Minus	FRNR	LMLI	Saturated buffers
Rule 3	Moderate	Low	DNB	SFMC	Two stage ditches

Rules↓	Inputs				Output
Operator →	IF	AND	AND	AND	Strategic option
Criteria →	Cost Effectiveness	Nitrogen Reduction Potential	Water Quality Improvement	Level of Acceptance	
Rule 6	Very High	Low	RRSP	LMLI	Saturated buffer
Rule 7	High	Low	SRNR	ACI	Saturated buffer

8.3.3 Fuzzy rule aggregation and defuzzification

The authors have fabricated different scenarios in the form of set of inputs for the classes under four criteria (i.e., CE, LOA) to highlight the effectiveness of the fuzzy expert system (Table 8.3). The inputs for the classes are then fed into the fuzzy expert system that proceed to trigger the relevant IF-THEN rules. The outputs of these rules are then aggregated to produce a consolidated membership function. The fuzzy output of this function is finally defuzzified using the centroid method (equation 8.3) to derive a crisp degree of suitability (Z) of the strategic option for given inputs.

8.3.4 Strategic perennial management for scenarios using fuzzy expert system

The proposed fuzzy-based expert system eases the watershed decision-making process by identifying the suitable strategic options for different input scenarios. The input values of the decision criteria are normalized and fuzzified using the membership function to incorporate the associated uncertainties. Table 8.3 illustrates some of the input scenarios developed in this study. The subsequent normalization and fuzzification of these crisp inputs and the fuzzy inference system outputs in terms of normalized strategic options values are presented in Table 8.4. Finally, the strategic options suitability percentages are obtained by first de-normalizing the fuzzy inference system output and simultaneously tracing back the suitability percentages from the output membership functions (Fig. 8.4). The final suitability percentage values for the strategic options corresponding to different input scenarios are summarized in Fig. 8.5.

For instance, in ‘scenario 1’, the desired water quality improvement includes maximum denitrification and biofiltration in addition to average flow reduction in both subsurface and surface pollutants which translates to a crisp score of 10.4 for WQI. This can also be observed by mapping the crisp input (10.4) to the fuzzy membership functions (i.e., FRNR) which was found to intersect FRNR, DNB, and SRNR fuzzy sets at 53.3%, 100% and 46.7% respectively. Also, in this scenario, the desired cost effectiveness is moderate (4.5 $/lb N). In the next step, different criteria values are normalized and fuzzified. For example, CE criteria value was normalized at the scale of ‘0-1’ resulting into a normalized CE index of 0.45 (Table 8.4). Similarly, the WQI was normalized at a scale of ‘0-1’ to obtain a normalized WQI score of 0.52. The normalized criteria values are then processed using fuzzy expert systems and suitable rules are fired for each scenario based on the respective membership functions. The outputs generated with respect to each rule are aggregated followed by defuzzification via centroid method. Finally, the crisp output value of 0.121 for ‘scenario 1’ was found to intersect the strategic option membership functions: depression storage and saturated buffer at 71.6% and 28.4% respectively (Fig. 8.5). Similarly, the results corresponding to other scenarios are attained (Fig. 8.6). A detailed discussion on these four scenarios and their corresponding results aimed at identifying a best possible combination of strategic options can be traced in the subsequent paragraphs.

‘Scenario 1’ depicts a situation wherein the decision maker wants only moderate profitability or cost effectiveness ($4.5 per lb N) and expects a moderate or little less than moderate nitrogen removal (35.6%), along with biofiltration, and reduction in flow. The planner is also prepared to provide incentives when conflicts arise. For these requirements, the fuzzy expert decision support model suggests a combination of two BMPs with a significant focus on the installation of depression storages (71.6%) and smaller focus on saturated buffers (28.4%). Mitsch and Day (2006) have recognized the use of depression storages or wetlands for the MRB region.

Also, several locations in the Midwest have showed successful application of wetlands (Crumpton et al., 2006). The suggested combination can be explained using the past research (Deletic and Fletcher, 2006; Lloyd et al., 2001; Zhao et al., 2016) which showed that the swales or the depression storages have good total suspended solids removal efficiency (68-93%) but relatively low nitrogen and phosphorus removal efficiency i.e., 7-50 % and 25-55% respectively which could be because of the ‘low retention time’ availability. However, the hydraulic retention time can be improved by increasing the length of the swales, but this practice turns uneconomical. Nonetheless, Zhao et al. (2016) suggests that swales can be ideal BMP for run-off pre-treatment in agricultural systems.

On the other hand, the saturated buffers are recognized as the effective and credible practices for reducing nitrate haul to adjacent stream or ditch (ADMC, 2019). The saturated buffers perturb the direct transport of agricultural drainage water from the tile lines and allow it to seep into the riparian buffer soil. Saturated buffers thus facilitate water quality improvement by maintaining the saturated soil condition, which supports anaerobic conditions necessary for the sustenance of denitrifying bacteria. Secondly, the saturated buffers enable consumption of the diverted drainage water and concomitant nitrate by vegetation roots present in the riparian buffer (Christianson et al., 2016). A study from nine sites conducted during September 2016 to 2017 in Iowa, Illinois, and Minnesota with saturated buffer installed reports consistent reduction of nitrate load from the agricultural drainage water (Brooks and Jaynes, 2017). The observed average nitrate load reduction from all sites was more than 60%, and the cost per pound nitrate removal was lower than any other nitrate-nitrogen removal approach (Table 8.1). Thus, the combination of saturated buffers (28.4%) and depression storages (71.6%) as suggested by the proposed fuzzy-based expert system is appropriate in addressing the simultaneous requirements concerning relatively high (> 35.6%) nitrate removal, biofiltration, flow reduction within the desired cost expenditure.

Table 8.3 Input scenarios to demonstrate proposed fuzzy expert system effectiveness

Scen--ario ↓	**CE ($/lbN)**	**NRP (% Removal)**	**WQI (%)**				**WQI (crisp)**	**LOA (%)**				**LOA (crisp)**
			RRSP	**FRNR**	**DNB**	**SRNR**		**CNHM**	**ACI**	**LMLI**	**SFMC**	
1	M (4.5)	M or MM (35.6)	---	53.3	100	46.7	10.4	100	36	---	---	3.72
2	MH * (3.5)	L or VL (6.7)	---	---	20	100	14.2	---	---	---	50	15.5
3	VH (1)	L (13.1)	---	---	---	100	15.3	5	57.5	100	---	8.85
4	M(5.2)	VL* (5.4)	100	40	---	---	2.2	80	100	40	---	6.6

**Corresponds to linguistic variables under criteria where only the prominent fuzzy membership function is selected.*

M – Moderate, MM – Moderate Minus, MH – Moderately High, L – Low, VL – Very Low, VH – Very High

Moreover, the percent combination of these two strategies can be spatially translated as quantitative land allocation of these two practices. For example, for a given 200 acres of wetland region to be denitrified with some reduction of flow, the land area with high nitrate removal requirement can be installed using saturated buffers (60 acres approx.), while the depression storages (140 acres approx.) can be installed in the area requiring flow reduction and biofiltration. Or there can be sequential (i.e., saturated buffer instalment following depression storages) implementation of the two strategies in the suggested land area coverages to meet the budgetary constraints. Similarly, in ‘scenario 2’, the decision make wants to procure moderately high (3.5 $/lb N) cost effectiveness but requires very low or low (6.7%) nitrogen reduction. However, the context necessitates strong prospects for flow reduction and support from the farmers, drainage managers and water conservation authorities. Considering above requirements, the fuzzy expert decision support model suggests installation of two-stage ditch system for the entire area. A two-stage ditch is a viable and economical solution for the locations where drainage ditches are already existing. The inclusion of vegetative floodplain in a two-stage ditch system design does not only stabilizes the stream banks and eliminates the need for regular dredging, but also provides increased residence time for agricultural drainage water, reduction of flow velocity, and shear stress (Christianson et al., 2016; Roley et al., 2016). D’Ambrosio et al. (2015) studied the geomorphic change of seven two-stage ditches after 3-10 years of construction in Ohio, Indiana, Minnesota states in Midwestern United States. The study highlights that the two-stage ditches require a minute routine maintenance. These attributes of two-stage ditch

Table 8.4 Normalized input scenarios and corresponding fuzzy inference system output (crisp score)

Decision criteria→ Scenario no.↓	CE	NRP	WQI	LOA	Strategic options (output or crisp score)
Scenario 1	0.450	0.712	0.520	0.186	Depression storage - 71.6% & Saturated Buffer - 28.4% (0.121)
Scenario 2	0.350	0.134	0.710	0.775	Two stage ditch (0.7)
Scenario 3	0.100	0.262	0.765	0.442	Saturated buffer (0.375)
Scenario 4	0.520	0.108	0.110	0.330	Two stage ditch - 56.4% & Riparian buffer – 79.5% (0.859)

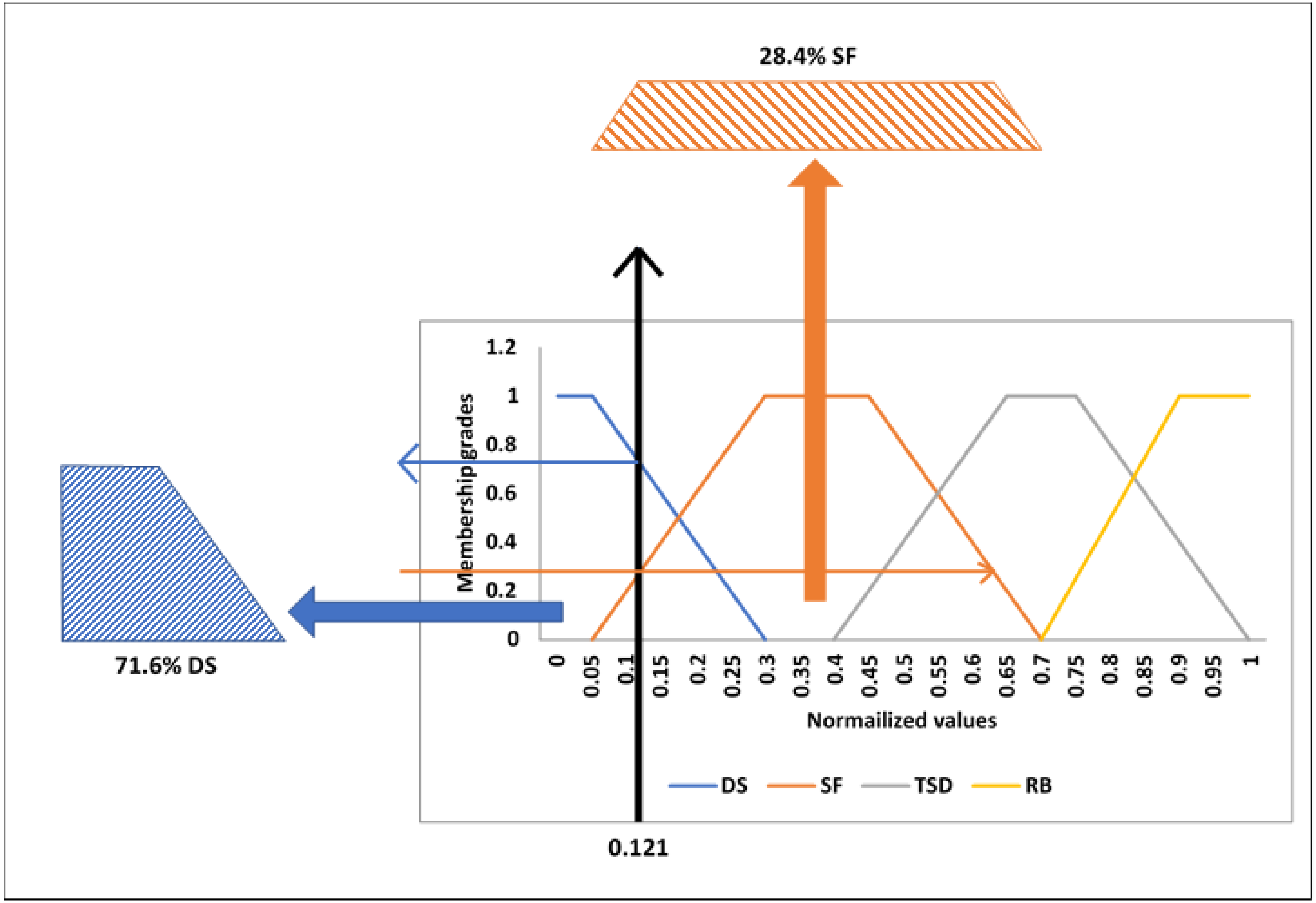


Fig. 8.5 An illustration for procuring strategic option percentages using ‘ Scenario 1’ crisp output obtained by employing fuzzy inference system

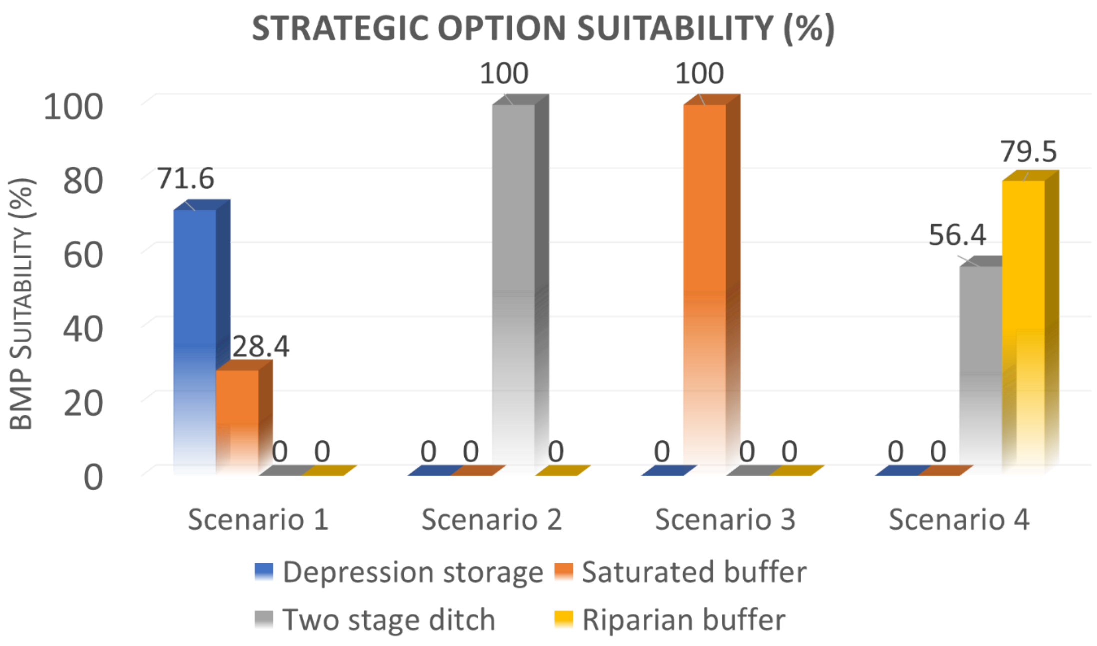


Fig. 8.6 Percentage suitability of BMPs under different scenarios

system attract the attention of farmers, drainage mangers, and water conservation authorities. Further, Christopher et al. (2017) and Roley et al. (2012) escalated the nitrogen removal efficiency of a two-stage ditch system and recommended 1 km stretch of two-stage ditch can reduce the nitrate-nitrogen load up to 20% even for high nitrate-nitrogen concentration.

For ‘scenario 3’, saturated buffer is recommended by the fuzzy expert system to satisfy the decision maker’s requirement of very high-cost effectiveness with a low nitrogen removal rate and run-off attenuation. Finally, the ‘scenario 4’ showcases the robustness and flexibility of the proposed model. Purposefully some obscure and uneconomical requirements are supplied to the fuzzy expert system i.e., almost a very low (5.4 %) nitrogen removal efficiency is demanded at relatively a bulkier cost (5.4 $/lb N) or moderate cost effectiveness. The model suggested implementation of ‘riparian buffers’ (79.5%) in conjunction with ‘two stage ditches’ (56.4%). The model justly captures the riparian buffer as the major choice, which ingest about an average 3 $/lb N for providing only 4.32% of nitrogen removal efficiency. Also, the proposition of sum of practices exceeds 100% (i.e., 79.5% + 56.4%) which is owing to the excessive cost invested by the decision maker for addressing small of nitrogen load removal. The fuzzy logic-based model not only suggests the BMPs for a given situation, but also guides the planning authorities on which combination of practices should be avoided while considering the uncertainties associated with the socio-economic and environmental criteria. The proposed model can be of the significant importance to the agricultural watershed planners and decision-makers towards the selection of pertinent field-scale nutrient management practices.

8.3.5 Perennial options for nitrate management in Indian agriculture system

The selection of perennial crop types for a region depends on various conditions such as climate, soil type, and water availability. The Napier grass (Pennisetum purpureum), Leucaena (Leucaena leucocephala), Bamboo (Bambusoideae), Banana (Musa spp.), Sapota (Manilkara zapota), and Drumstick (Moringa oleifera) are some of the viable perennial options for Uttar Pradesh, India considering its diverse climate (Summers: 35°C to 45°C and Winters: below 5°C to 20°C), varying soil types (alluvial, sandy, black soils), and the typical rainfall patterns. The perennial options for nitrate management have gained recognition in recent years in the USA while being practiced for decades. The conservation reserve program (CRP), administered by USDA, has specifically supported perennial crops through financial incentivization converting erosion/ecologically vulnerable lands to perennial covers. Cottonwood, hazelnut, willows, and prairie cordgrass are perennials prevalent in the USA. Conservation practices like riparian buffers and retention ditches are not widespread/standard in Muzaffarnagar (a district in Uttar Pradesh) (Appendix-B, Questionnaire B 2.3). However, prevalent practices such as vegetative barriers and terracing could be applied with appropriate perennial covers. The practices such as riparian buffers and two-stage ditch could gain traction provided there is financial support/policy frameworks from the Indian government and resolution of issues such as small landholding, limited resource availability, and reliance on local practices through knowledge-sharing (workshops, training, field demonstrations) and incentivization. Thus, learning from successful nations (like the USA), perennial options in integration with suitable BMPs also have sufficient latitude in India. In addition, the proposed fuzzy-based system permitting the use of qualitative as well as uncertain inputs could positively support the effective selection of perennial options.

8.4 Summary

The upper Mississippi River basin has been identified as the most significant contributor of excessive nutrients to the hypoxic zone in the Gulf of Mexico. The land-use changes from an internally drained prairie-wetland complex to an intensively managed corn-soybean production system drained by subsurface tile drainage system in the north-central Iowa and south-central Minnesota are the primary cause of nutrient loads into the Mississippi River and many other environmental stresses. The present study summarizes the water-quality degradation from land-use change and offers a fuzzy logic-based decision support for assessing degree of suitability of the four recommended perennial plant options for managing water and nitrate-nitrogen export. These options are designed based on landscape position that currently fails to produce high yielding row crops and scale: (1) marginal upland depressions for water storage by planting deep-rooted perennial grasses and fast-growing woody poplar, willow, and alder in poorly drained swales; (2) saturated buffers and/or subtle changes in landscape slope for draining high nitrate-nitrogen subsurface (through multi-species phytoremediation treatment buffers or strips of perennial vegetation); (3) two-stage ditches with linear floodplains planted with perennial grasses; and (4) riparian and in-channel ecologically engineered trees, shrubs, and grasses to better connect meander belt width to frequent peak stream flows at larger scales. When applied throughout a typical Des Moines lobe till watershed, each option can have positive cumulative environmental effects. Fuzzy logic enhanced the precision in watershed decision-making by incorporating the uncertainty associated with factors like cost effectiveness, nitrate reduction potential, water quality improvement, and level of acceptance.

CHAPTER 9

SUMMARY CONCLUSIONS & FUTURE SCOPE

9.1 Conclusions

The present research work suggests various models/frameworks for promptly targeting the immediate need of agricultural non-point source pollution control facilitated by the incorporation of farmer/landholders' and local stakeholders' opinion. The models/frameworks utilized the contemporary technological advancements in the form of soft computing (i.e., fuzzy logic, optimizing techniques, etc.), remote sensing, geographical information system, watershed-scale hydrological models, and learnings from the state-of-the-art practices in USA encompassing the use of novel modeling techniques and best management practices. The importance of the river waters; their deterioration by anthropogenic influences; the initiatives taken by the national governments in handling this issue, in particular, India; the methods adopted by the advanced nations like US and EU for riverine ecosystem management; and the use of current technologies for addressing this intimidating issue have been discussed in the introduction (1st chapter) of this synthesis. Additionally, the major contributions and organization of the present research have also been discussed.

The various conservation practices, models, and technologies their applications in the research work related to NPS modelling at the watershed-scale have been discussed in the Chapter 2 of this work. Majorly, the literature review critiques the conservation practices or BMPs under the source, process, and end control approaches of ANPS pollution management. Consequently, the watershed scale hydrological models for ANPS pollution assessment were discussed. There has been significant research conducted in developing innovative models and tools for assessing, predicting, and managing the non- point source pollution by suggesting effective implementation plans for the conservation practices utilising, soft computing techniques such as fuzzy-based tools, heuristic algorithms, and watershed modelling tools like SWAT, HSPF, AGNPS, etc. However, the contemporary research work while proposing the conservation practices for a watershed system, does not consider the economic, agronomical, socioeconomic, hydrological, and ecological factors simultaneously that in essence prevents the in-field implementation of these practices. In order to find a reliable optimisation method for the placement of BMPs in a watershed system, researchers are now working on new models with various combinations of search algorithms. The research to find an appropriate BMP (taking into account both structural and non-structural BMPs) at a field-scale in the Indian context is quite scarce. Additionally, there is still a dearth of research on the selection of BMPs that satisfy economic and socioeconomic considerations. Consequently, the identified research gaps, research objectives, and scope were discussed in chapter 3.

Various innovative modelling frameworks through the course of developing chapters 4, 5, 6, 7, and 8. These modelling frameworks provide decision support for comprehensive handling of agricultural non-point source pollution by leveraging the application of source, process and end control BMPs or by considering both the structural and non-structural BMPs and the related agronomic, socioeconomic, hydrological, as well as economic factors while suggesting the conservation practices for a landscape. Each of these chapters significantly and uniquely contributes towards the achievement of this goal by explicitly defining the problem, developing effective methodology, and their successful demonstrations for the selected study locations in India and United States. The key contributions from this thesis and consequent fulfilment of the identified research gaps (as stated in the literature review) are discussed as follows:

- Integrated tool for crop rotation practices allocation:

  The crop rotation practices are one of the important techniques for the source control of ANPS pollution. The integrated application of geoinformatics, stochastic pairwise comparison, and constrained optimization methods can help in scientific allocation of the crop rotation patterns to potential land parcels by the way of evaluating land’s strengths and weaknesses as per the specific crop’s requirements. This additionally helps in avoiding the severe repercussions of inappropriate decisions related to agricultural land-use planning on soil health, water resources, food security, and economic crisis. The approach enables management of a wide variety of multi-spatial data under the fields of climatology, topography, and soil properties, generates classified criterion layers, standardizes, and overlays them. The use of SPC is especially advantageous in providing flexibility to the decision maker(s) in providing their opinions while ranking the criteria. Further, the infusion of constraint optimization assists farmers and other stakeholders in subjective selection of crop rotation patterns based on profit maximization and water conservation. The analytical study of three scenarios in the 4^{rth} Chapter revealed that the annual average cultivation increment and decrement of maize, mustard, and sugarcane crops describe the profit as well as water conservation potential of the agricultural land in Muzaffarnagar, respectively. The results also highlighted many important facts such as: (1) Even for retrieving maximum profits, not more than 20% of land should be allocated for sugarcane cultivation (90% at present); (2) Mustard, potato, maize, and sorghum also have good cultivation potential which are currently not given due consideration in Muzaffarnagar. The inclusion of interactive web-based dashboard sets a common interface for farmers, planners, and government officials where the knowledgebase, opinions, and conflicts related to the cropping pattern selection could be mutually shared. Thus, the proposed tool is a robust framework which simultaneously considers multitudes of factors: soil nutrients, terrain characteristics, crop requirements, hydrology, economics and promotes the sustainable agricultural land-use planning through field scale implementation of optimized crop rotation patterns.

Research gaps accomplished:

1.) Suggested crop rotation patterns consider economical, agronomical, hydrological, ecological, and socioeconomical aspects while suggesting BMPs for the study watershed.
2.) Constraint optimization technique utilization to render sustainable crop rotations patterns.
3.) Web-based dashboard that presents various applicable crop rotation patters promoting their field scale implementation.
4.) Developed web-based dashboard could serve as common platform for discussions and knowledge transfer among farmers, watershed planners.

- Graph-networking and farmer adoption-based effective integrated agrarian conservation practices targeting:

The pollution in the river Ganges is ever increasing and many action plans and pledges promising bringing Ganges water to the pure state have failed, like a cascade, one after another. With about 50% of Indian population dependent on the water of Ganges, the effective/promising cleansing techniques implementations can't wait any further. Thus, the present research proposes an immediate remedial action technique for controlling the agricultural non-point source pollution (one of the significant pollution source) transfer to the River Ganges. It integrates the concept of farmer conservation identity and a novel graph network-based optimization with the vitality of a robust hydrological and BMP simulation model, SWAT for the prompt adoption of effective BMPs along with their on-ground placement propositions. The graph network approach enables the selection of integrated BMPs that can aid in mutually offsetting or settlement of limitations each of the selected practices. Further, the consideration of farmer's conservation identity enabling capturing of the farmers' willingness towards BMP adoption, who are the sole ultimate BMP adoption decision makers and maintainers, directs the effective placement of the proposed BMPs. The proposed approach demonstrated for 8510 km^2 agriculture intensive watershed draining in Hindon River (a tributary of Yamuna) recommends the implementation of the (BMPs applicable for the study region) riparian buffers in conjunction with conservation tillage to the subbasins influenced by the Morna subdistrict in the study area to retrieve the maximum nitrate reduction efficiency (0.28), i.e., the ratio of nitrate reduction (kg) to the total BMP cost ($) followed by the application of conservation tillage and nutrient management (0.23); and riparian buffer and nutrient management (0.17). The analytical study of the four scenarios including base scenario also revealed that consideration of critical nitrate subbasins alone for BMP targeting is insufficient. Further, studying the effects of BMPs performance on the nutrient or pollution reduction could be highly misleading (depicted by the real values under Base scenario in Table 5.6) if the farmers' behavioural response factor is not included in the analysis. Thus, the proposed framework for BMP planning and targeting could be valuable guide for the researchers, watershed planners, government policy makers for delivering sustainable and prompt conservation practices implementation suggestions.

<u>Research gaps accomplished:</u>

1.) The developed framework considers economical, agronomical (landuse patter and cultivated crops), hydrological, ecological, and socioeconomical aspects for targeting BMPs.
2.) Graph-network based optimization for developing optimized and integrated BMPs.
3.) The consideration of farmers' conservation consciousness encourage field scale implementation of the BMPs.

- Tool for identifying the core precision agriculture implementation challenges:

  The precision agriculture in addition to aiding ANPS control and thus facilitating thorough pollution reduction, brings numerous benefits to the farming industry, including increased efficiency, productivity, and profitability. By using sensors, GPS, and other advanced technology, precision agriculture allows farmers to monitor and manage their crops and land in real time, leading to more informed decision-making and better overall results. However, there are immense challenges and limitations to the adoption of precision agriculture as demonstrated in this study. The developed approach deals with these challenges in a systematic manner to ensure on-ground implementation of PAT. One of the main barriers is the cost of implementing the technology and infrastructure required for precision farming. This can also be a significant expense for farmers having small land holdings, who may not get the desired return on investments from the implementation of the PATs. Additionally, there is a learning curve associated with using precision agriculture, and some farmers may be hesitant to adopt new technology and techniques. In order to address these challenges and facilitate the adoption of precision agriculture, the study recommends the following:

  - Develop cost-effective solutions and technologies for precision agriculture, such as affordable sensors and GPS systems, to make it more accessible to small farmers
  - Provide training and support programs to help farmers learn how to use precision agriculture technology and techniques
  - Create incentives and support programs, such as grants and subsidies, to help farmers cover the costs of implementing precision agriculture
  - Conduct further research to understand the potential benefits and limitations of precision agriculture and develop strategies to maximize its potential and overcome its challenges.
  - Work with governments and industry organizations to establish guidelines and regulations for the use of precision agriculture technology, to ensure its safe and responsible implementation.
  - Collaborate with other stakeholders, such as universities and research institutions, to advance the development and adoption of precision agriculture.
  - Educate the public about the benefits of precision agriculture and promote its adoption to support the sustainability and success of the farming industry.

Overall, the adoption of precision agriculture has the potential to bring significant benefits to the farming industry and improve the sustainability and efficiency of agricultural production. By implementing these recommendations, the transition to precision agriculture can be facilitated and their potential could be realized.

Research gaps accomplished:

1.) The basic events explored in the study considers factor from economical, agronomical, hydrological, ecological, and socioeconomical aspects.
2.) The identification of basic events causing failure of the top event and analysis of different scenarios reveals key solutions that can improve the field scale adoption of conservation practices.
3.) The framework engages and considers the viewpoint of experts of different domains, i.e., agriculture, academics, working professionals, and students.

- Cost-effective integration of conservation practices for achieving TMDL goals:

  HSPF-SAM, comprising the use of GIS, BMP databases, and analysis and optimization tools, delivers timely (in minutes) and accurate estimates of pollutant sources and inclusive watershed treatment plans in an economically sound manner. The simplified SAM analysis promotes the simultaneous incorporation of local watershed planners' and natural resource managers' knowledge. SAM is vital in analysing and developing economically targeted conservation solutions for attaining TMDL for phosphorus and sediment pollutants exemplified through a case study of the Dry Wood Creek watershed. The case study demonstrated that among the seven selected relevant BMPs, Conservation Cover Perennials and Conservation Crop Rotation delivered the maximum reduction in phosphorus and sediment (46% and 37% of the target TMDL) loads alongside consuming the maximum budget (79% of the total budget). While Field Strips and Reduced Tillage were the most efficient, however, contributing only about 20% in reducing both pollutions pertaining to their low reference suitability. The inability of individual BMPs towards TMDL attainment underscored BMP integration. Thus, the integrated and optimized case scenarios developed entailed approximate achievement of TMDL under budget through rendering a cost-effective and integrated rank list of BMPs for the watershed basins. This also highlighted the importance of farmer participation (minimum 83.7% for this case) for meeting the target limits. The information on spatial or geographic BMP placement, in addition to the theoretical assignment of BMPs to the basins; and the added availability of features: farmer participation, climatic factor, reference suitability, and efficiencies of the BMP at the final stage in the SAM framework, however, could serve to further enhance and expedite SAM's decision-making potential. Conclusively, SAM is a powerful, robust, and easy-to-learn tool that can abridge the knowledge transfer between local watershed managers and expert modelers and thus extend the use of publicly supported HSPF to support TMDL and Watershed Restoration and Planning Strategies reports on field implementation.

Research gaps accomplished:

1.) HSPF-SAM model evaluated in 7th chapter considers economical, agronomical, hydrological, ecological, and socioeconomical aspects.
2.) The various case scenarios were optimized using the target functionality in SAM.
3.) Rendering of cost-effective and integrated rank list of BMPs for the watershed sub-basins encourages field-scale implementation of BMPs.
4.) SAM especially excludes the requirements of modeling skills and thus encourages the participation of non-modeling users.

- Fuzzy-based tool for strategic targeting of BMPs under data scarce scenarios:

In Chapter 8, the strategic placement of four perennial vegetation practices viz. depression storages, two-stage ditches, saturated buffers, and riparian buffers were exemplified using the proposed tool. The proposed fuzzy-based tool served to overcome the lack of quantitative records and ambiguity concerning the performance of the suggested options inhibiting the decision-making process or the selection of a suitable strategy to limit the environmental damage. The proposed fuzzy logic-based expert system simplified the decision-making process with simultaneous management of the uncertainties salient to the decision criteria. The four different scenarios analyzed in the 8th chapter represented a wide range of conditions possible in the study area pertaining to the four criteria (i.e., Cost Effectiveness, Nitrate Reduction Potential, Water Quality Improvement, and Level of Acceptance). The proposed model propounded application of depression storage - 71.6% and saturated buffer - 28.4% for the criteria corresponding to scenario 1. This revealed the tool's efficacy in suggesting a mix of strategic options with good precision. Similarly, the two-stage ditch (100%) and saturated buffer (100%) were suggested by the tool for Scenario 2 and 3 respectively in the 7th chapter. The discussion on scenarios substantiated the tool's ability to integrate linguistic responses (i.e., Level of Acceptance and Water Quality Improvement) with associated subjectivities and uncertainties to the quantitative criteria (i.e., Cost Effectiveness and Nitrogen Reduction Potential).

Research gaps accomplished:

1.) The flexible fuzzy-based approach allows consideration of various quantitative and qualitative aspects for delivering the suitable combination of BMPs.
2.) The simple and robust approach could suggest BMPs on the field as well watershed-scale depending on the parameters' selection and rule formulation.
3.) The questionnaire survey conducted includes consent from local farmers, academicians, watershed planners.

By contrasting the proposed frameworks with past official and non-governmental efforts for non-point source pollution abatement as well as a few secondary sources, all of the results from the proposed models have been validated. Although the models and the scenarios have been demonstrated for the Ganga/Yamuna River basin in India and the Upper Mississippi basin in the USA, input scenarios can be developed based on the characteristics of any watershed and processed in the model to aid decision-making based on water quality and economic goals.

9.2 Key salient features

Following are the major salient features of the present thesis:

1.) Suggests frameworks that can be readily integrated with AI-based tools for making sound decisions to promptly target the need of ANPS pollution control
2.) Drawing parallels among Indian and USA watersheds for on-ground implementation of BMPs to control NPS in India
3.) Leveraging source, process, and end control BMPs application considering agronomic, socioeconomic, hydrological, and economic factors
4.) Utilization of contemporary technological advancements: soft computing (i.e., fuzzy logic, optimizing techniques, etc.), RS, GIS, watershed-scale hydrological models
5.) Farmers' and local stakeholders' driven clear roadmap to implement precision agriculture techniques in Indian watersheds
6.) Web-based dashboard to guide practitioners toward adopting crop rotation practices in the study area for minizing irrigation and maximizing profits

9.3 Limitations and future work

The study performed advanced analysis on multi-layered spatial data using GIS and remote sensing technology, statistical, optimization and hydrological models. The analysis employed an array of flexible mathematical tools & models to attain the sustainable conservation practices. The uncertainties associated with stakeholders and input data have been adequately dealt by the infusion of fuzzy logic in the developed decision support tools. However, there are several considerations which could also be of great importance, such as, to ensure and support policy making for national food security that can be deliberated by the future studies. The major ones are discussed below:

- Considering the impacts of climate change, including alterations in precipitation patterns, temperature fluctuations, shifts in nutrient cycling, and elevated risks of soil erosion, can be of significant importance in developing a resilient model for BMP targeting.
- The data collected and prepared by the geospatial agencies and organizations (like USDA, NRCS) through field surveys, collaborations with research institutions and government/non-government organizations can be an invaluable asset for improving the decision support effectiveness, enhancing the accuracy, efficiency, and reliability of the proposed models. For instance, USDA, NRCS maintains data on various conservation practices, i.e., their present in-field adoption, their performance over the years etc. Incorporation of such information database in the proposed models can not only validate and cross-check the competency of the results suggested by the models but would also eliminate the redundant suggestions (already existing in the fields). In Indian context, however, there is lack of such detailed farm level datasets including farm-level crop specific information, conservation practices and their performances, detailed land use land cover information. The adaption to such technological advances as used by nations like USA for collecting field scale datasets can elevate the conservation potential of Indian watersheds.
- The use of contemporary Artificial Intelligence (AI) advancements like ChatGPT can be enormously rewarding for handling ANPS pollution. As there are complex interrelationships among the vast inventory of participating factors which can influence the pollution generation, transportation and their control through applied practices. The watershed models, how accurate they may be, cannot capture all interrelationships occurring in the natural environment. AI models could be trained

through vast environmental (rainfall, temperature patterns), agricultural datasets (fertilizer application, crop requirements), and water quality information. And prediction on the pollution intensity and locations could be effectively made. AI can also assist farmers in precision agriculture through integrated real-time monitoring of the weather, crop requirements and consequent real time decisions can be furthered across the farmers through a trained ChatGPT chatbot assistant.

- Further, incorporating Internet of Things (IoT) and sensors for real-time monitoring could expedite the data collection of soil and plant nutrient levels, crop health, and pest attack level. It could assist in the real-time optimization of fertilizers, pesticides, and herbicide applications.
- The use of flood modelling techniques or flood scenario simulation could help in identification of areas susceptible to erosion and runoff and serve towards selection of erosion control practices.
- As the modern agriculture steps more into utilization of digitized data, the profound data immutability and data integrity features of recent Blockchain technology could ensure transparent and reliable data storage related to in-field fertilizer application rates, use of land management and irrigation techniques, etc. enabling improved identification of sources contributing NPS pollution. Blockchain tool could also be useful in terms of its attribute of facilitating decentralized collaboration of stakeholders. Utilizing which different stakeholders such as farmers, watershed planners, researchers, and politicians can access identical/real/transparent information and coordinate their efforts in mitigating NPS pollution.
- Higher resolution datasets, advanced optimization techniques such as ant colony optimization, particle swarm optimization, etc. could also be implemented for attaining better sustainable solutions.

9.4 Concluding remarks

Overall, the thesis attempts to integrate scientific data/information, academic research, and farmers, local stakeholders, and watershed experts’ opinions for developing effective, simple, and efficient frameworks for decision support for the selected watersheds of India and USA. The thesis delivers significant benefits both at the societal as well as scientific platforms, these are summarized in Table 9.1. Versatile methodologies have been adopted while developing the proposed models/frameworks in this thesis which allows editing, addition, and removal of the input datasets. Thus, the proposed tools are globally applicable and can be modified/developed for any agricultural watershed provided the availability of fundamental datasets and knowledge on the local agricultural system.

Table 9.1 Societal and Scientific application of the work

Societal	Scientific
• Enduring increase in farmer income by virtue of advancing soil health and increasing production	• Inclusion of smart agriculture techniques setting forth platform to facilitate effective use of advanced artificial intelligence, remote sensing and modeling techniques
• Preserving natural resources such as water quality, land/soil resources, and biodiversity	• Techniques that enable the incorporation of farmers' perspectives, improve knowledge transfer, and implementation of BMPs
• Suggesting scientific and versatile models to promote sustainable agriculture	• Development of novel techniques for integrating BMPs and optimizing synergy
• Systematic guidelines for the landowners, governmental and non-governmental pollution agencies, and water resource planners for implementing best management practices	• Handling of uncertainties associated with the various geodatabases, other data sources, and experts’ opinions

The findings of this thesis offer valuable insights for the researchers, academicians, local communities, scientists, and farmers towards the sustainable and prompt implementation of conservation practices and precision agriculture techniques.

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APPENDIX-A

AUXILIARY INFORMATION TO THE RESEARCH ANALYSIS

The work presented in the aforementioned chapters involves the use of numerous analysis/computations on the datasets procured from various sources. The information concerning these computations has been presented through the following sections AUX. 1 and AUX. 2

AUX.1 Analysis information presentation using tabular datasets

Table A1 Net return, total water consumption, and acreage for the crop-rotation patterns under maximum net return scenario

Maximization of Income Return	Acreage (ha x 1000)	Total Water Consumption (Mm^3)	Net Return (Million $)
Sorghum-Wheat-Fallow	33.26	243.89	10.67
Rice-Potato-Sugarcane-Wheat-Fallow	28.51	424.85	32.75
Rice-Potato-Maize-Potato-Fallow	0.19	1.88	0.20
Maize-Potato-Sugarcane-Fallow	154.22	2506.09	186.88
NSP	44.53	0	0
Total	260.72	3176.71	230.50

Table A2 Conversion of the linguistic variables into fuzzy values

Linguistic Variable	Fuzzy Number	Reciprocal Fuzzy
Very Low (VL)	(1,1,2)	(0.5,1,1)
Low (L)	(1,2.5,4)	(0.25,0.4,1)
Medium (M)	(3,5,7)	(0.142,0.2,0.33)
High (H)	(6,7.5,9)	(0.11,0.133,0.166)
Very High (VH)	(8,9,9)	(0.11,0.11,0.125)

Table A3 Opinions of the eight experts summarized for 21 basic events

Basic Event	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8
BE1	High	Medium	High	Very High	High	Very High	Very High	High
BE2	High	Very High	Medium	High	Very High	Very High	Medium	High
BE3	Medium	Low	Medium	High	High	High	Medium	High
BE4	Medium	High	Medium	High	Medium	High	Medium	High
BE5	High	High	High	Medium	Medium	Medium	Low	Medium
BE6	High	Medium	Medium	High	Medium	High	High	High
BE7	Medium	Medium	Medium	High	High	High	Medium	Medium
BE8	Medium	Medium	High	Medium	Medium	Low	High	High
BE9	Low	High	High	Medium	High	Medium	High	High
BE10	Medium	High	High	High	High	Medium	High	High
BE11	Medium	Very High	High	High	Very High	Very High	High	Very High
BE12	Very Low	Very High	Medium	Very High	High	Very High	Medium	High
BE13	Medium	High	High	High	High	High	High	High
BE14	High	Very High	Medium	Very High	High	Very High	Medium	High
BE15	Low	High	High	High	High	Medium	High	High
BE16	Low	High	High	High	High	Medium	High	High
BE17	Medium	High	Medium	Very High	Medium	Very High	Very High	High
BE18	Very High	Very High	High	Very High	High	Very High	High	High
BE19	Medium	Very High	Medium	High	High	Very High	Medium	Very High
BE20	Very High	Very High	Medium	High	High	Medium	Medium	Very High
BE21	High	Very High	Medium	Very High	Medium	High	High	High

Table A4 Experts and their weighing factors

Expert No.	Title	Experience (years)	Education level	Age (years)	Weighting score	Weighting factor
1	Academician or Scientist	10-20	Doctoral	30-40	5+3+5+3=16	0.144
2	Student	<5	Bachelors	<25	1+1+3+1=6	0.054
3	Farmer	20-30	School	>50	5+4+2+5=16	0.144
4	Academician or Scientist	10-20	Doctoral	30-40	3+3+5+3=14	0.126
5	Agricultural Expert	10-20	Masters	30-40	5+3+4+3=15	0.135
6	Farmer	>30	Uneducated	>50	5+5+1+5=16	0.144

Expert No.	Title	Experience (years)	Education level	Age (years)	Weighting score	Weighting factor
7	President of the International Society of Precision Agriculture	20-30	Doctoral	40-50	2+4+5+4=15	0.135
8	Farmer	10-20	School	30-40	5+3+2+3=13	0.117
		Sum			111	1.000

Table A5 Weighing attributes to calculate the weighing factors

Attributes→ Title/Designation↓	**Experience in years**	**Education level**	**Age in years**	**Weight**
Farmer	>30	Doctoral	>50	5
Agricultural Expert	20-30	Masters	40-50	4
Academician or Scientist	10-20	Bachelors	30-40	3
Working Professional	5-10	School	25-30	2
Student	<5	Uneducated	<25	1

Table A6 Integrated and optimized allocation BMPs to Dy Wood Creek watershed basins for case 1

Location:	A210			
Parameter:	Total Phosphorus (lbs/yearl)			
Statistic:	% Reduction Base			
Target:	73.1%			
Budget:	Null			
Rank of cost effectiveness	**Progress to target (%)**	**Cost ($)**	**Basin**	**BMP**
1	4.617	80126	A210	Water and Sediment Control Basin (Cropland)
2	2.902	77132	A210	Nutrient Management + Manure Incorporation
3	2.623	87018	A220	Water and Sediment Control Basin (Cropland)

`

Rank of cost effectiveness	**Progress to target (%)**	**Cost ($)**	**Basin**	**BMP**
4	1.446	48127	A230	Water and Sediment Control Basin (Cropland)
5	14.619	697988	A210	Conservation Cover Perennials
6	3.963	145014	A250	Water and Sediment Control Basin (Cropland)
7	0.739	27986	A240	Water and Sediment Control Basin (Cropland)
8	1.973	259019	A210	Conservation Crop Rotation
9	0.972	48914	A230	Nutrient Management + Manure Incorporation
10	1.763	88441	A220	Nutrient Management + Manure Incorporation
11	2.283	129372	A250	Nutrient Management + Manure Incorporation
12	0.575	32199	A240	Nutrient Management + Manure Incorporation
13	8.834	801378	A220	Conservation Cover Perennials
14	4.829	443214	A230	Conservation Cover Perennials
15	1.172	296998	A220	Conservation Crop Rotation
16	0.615	164259	A230	Conservation Crop Rotation
17	11.293	1172258	A250	Conservation Cover Perennials
18	2.942	296786	A240	Conservation Cover Perennials
19	1.409	434449	A250	Conservation Crop Rotation
20	0.395	109991	A240	Conservation Crop Rotation
21	0.162	40487	A260	Water and Sediment Control Basin (Cropland)
22	0.331	87599	A270	Water and Sediment Control Basin (Cropland)
23	0.126	46582	A260	Nutrient Management + Manure Incorporation
24	0.258	100787	A270	Nutrient Management + Manure Incorporation
25	0.644	429361	A260	Conservation Cover Perennials
26	0.0863	159125	A260	Conservation Crop Rotation
27	1.311	928977	A270	Conservation Cover Perennials
28	0.173	344287	A270	Conservation Crop Rotation
Total	**73.0553**	**7577874**		

Table A7 Integrated and optimized allocation BMPs to Dy Wood Creek watershed basins for CASE 2

Location: A210
Parameter: Total Phosphorus (lbs/year)
Statistic: % Reduction Base
Target: Null
Budget: Null

Rank of cost effectiveness	Progress to target (%)	Cost ($)	Basin	BMP
1	2.784	11981	A210	Reduced Tillage (no-till)
2	2.729	16222	A210	Filter Strips, 50 ft wide (Cropland field edge)
3	1.926	15848	A220	Reduced Tillage (no-till)
4	1.062	8765	A230	Reduced Tillage (no-till)
5	3.842	39183	A210	Riparian Buffers, 100 ft wide (replacing row crops)
6	3.237	29380	A250	Reduced Tillage (no-till)
7	0.606	5686	A240	Reduced Tillage (no-till)
8	1.284	14843	A220	Filter Strips, 50 ft wide (Cropland field edge)
9	0.705	8209	A230	Filter Strips, 50 ft wide (Cropland field edge)
10	2.374	31456	A250	Filter Strips, 50 ft wide (Cropland field edge)
11	0.301	3951	A240	Filter Strips, 50 ft wide (Cropland field edge)
12	1.847	35853	A220	Riparian Buffers, 100 ft wide (replacing row crops)
13	1.012	19829	A230	Riparian Buffers, 100 ft wide (replacing row crops)
14	3.306	82180	A210	Water and Sediment Control Basin (Cropland)
15	3.271	75980	A250	Riparian Buffers, 100 ft wide (replacing row crops)
16	0.443	9542	A240	Riparian Buffers, 100 ft wide (replacing row crops)
17	2.07	79110	A210	Nutrient Management + Manure Incorporation
18	1.953	89249	A220	Water and Sediment Control Basin (Cropland)
19	1.068	49361	A230	Water and Sediment Control Basin (Cropland)
20	2.537	148732	A250	Water and Sediment Control Basin (Cropland)

Rank of cost effectiveness	Progress to target (%)	Cost ($)	Basin	BMP
21	0.588	28703	A240	Water and Sediment Control Basin (Cropland)
22	0.715	50168	A230	Nutrient Management + Manure Incorporation
23	1.307	90709	A220	Nutrient Management + Manure Incorporation
24	1.455	132689	A250	Nutrient Management + Manure Incorporation
25	0.456	33025	A240	Nutrient Management + Manure Incorporation
26	0.133	8227	A260	Reduced Tillage (no-till)
27	0.271	17799	A270	Reduced Tillage (no-till)
28	0.0659	5715	A260	Filter Strips, 50 ft wide (Cropland field edge)
29	0.134	12366	A270	Filter Strips, 50 ft wide (Cropland field edge)
30	0.097	13805	A260	Riparian Buffers, 100 ft wide (replacing row crops)
31	0.198	29868	A270	Riparian Buffers, 100 ft wide (replacing row crops)
32	0.129	41525	A260	Water and Sediment Control Basin (Cropland)
33	0.262	89845	A270	Water and Sediment Control Basin (Cropland)
34	0.1	47777	A260	Nutrient Management + Manure Incorporation
35	0.204	103371	A270	Nutrient Management + Manure Incorporation
Total	**44.4719**	**1480952**		

Table A8 Integrated and optimized allocation BMPs to Dy Wood Creek watershed basins for case 4

Location:	A210
Parameter:	Total Phosphorus (lbs/year)
Statistic:	% Reduction Base
Target:	Null
Budget:	Null

Rank of cost effectiveness	Progress to target (%)	Cost ($)	Basin	BMP
1	2.33	10028	A210	Reduced Tillage (no-till)
2	2.321	13578	A210	Filter Strips, 50 ft wide (Cropland field edge)

Rank of cost effectiveness	Progress to target (%)	Cost ($)	Basin	BMP
3	1.612	13265	A220	Reduced Tillage (no-till)
4	0.889	7336	A230	Reduced Tillage (no-till)
5	3.324	32796	A210	Riparian Buffers, 100 ft wide (replacing row crops)
6	2.709	24591	A250	Reduced Tillage (no-till)
7	0.507	4760	A240	Reduced Tillage (no-till)
8	1.096	12424	A220	Filter Strips, 50 ft wide (Cropland field edge)
9	0.602	6871	A230	Filter Strips, 50 ft wide (Cropland field edge)
10	2.039	26329	A250	Filter Strips, 50 ft wide (Cropland field edge)
11	0.257	3307	A240	Filter Strips, 50 ft wide (Cropland field edge)
12	1.597	30009	A220	Riparian Buffers, 100 ft wide (replacing row crops)
13	0.876	16597	A230	Riparian Buffers, 100 ft wide (replacing row crops)
14	2.943	68785	A210	Water and Sediment Control Basin (Cropland)
15	2.869	63595	A250	Riparian Buffers, 100 ft wide (replacing row crops)
16	0.381	7987	A240	Riparian Buffers, 100 ft wide (replacing row crops)
17	1.897	66215	A210	Nutrient Management + Manure Incorporation
18	1.726	74702	A220	Water and Sediment Control Basin (Cropland)
19	0.945	41315	A230	Water and Sediment Control Basin (Cropland)
20	9.747	599196	A210	Conservation Cover Perennials
21	2.305	124489	A250	Water and Sediment Control Basin (Cropland)
22	0.514	24025	A240	Water and Sediment Control Basin (Cropland)
23	1.633	222358	A210	Conservation Crop Rotation
24	0.651	41991	A230	Nutrient Management + Manure Incorporation
25	1.187	75923	A220	Nutrient Management + Manure Incorporation
26	1.366	111061	A250	Nutrient Management + Manure Incorporation
27	0.408	27642	A240	Nutrient Management + Manure Incorporation
28	0.111	6886	A260	Reduced Tillage (no-till)
29	0.227	14898	A270	Reduced Tillage (no-till)
30	6.07	687953	A220	Conservation Cover Perennials

Rank of cost effectiveness	Progress to target (%)	Cost ($)	Basin	BMP
31	3.3	380482	A230	Conservation Cover Perennials
32	1.003	254961	A220	Conservation Crop Rotation
33	0.529	141010	A230	Conservation Crop Rotation
34	6.904	1006338	A250	Conservation Cover Perennials
35	0.0561	4784	A260	Filter Strips, 50 ft wide (Cropland field edge)
36	2.126	254779	A240	Conservation Cover Perennials
37	1.096	372958	A250	Conservation Crop Rotation
38	0.115	10350	A270	Filter Strips, 50 ft wide (Cropland field edge)
39	0.353	94423	A240	Conservation Crop Rotation
40	0.0835	11555	A260	Riparian Buffers, 100 ft wide (replacing row crops)
41	0.17	25000	A270	Riparian Buffers, 100 ft wide (replacing row crops)
42	0.113	34756	A260	Water and Sediment Control Basin (Cropland)
43	0.229	75200	A270	Water and Sediment Control Basin (Cropland)
44	0.0895	39989	A260	Nutrient Management + Manure Incorporation
45	0.183	86521	A270	Nutrient Management + Manure Incorporation
46	0.465	368590	A260	Conservation Cover Perennials
47	0.0772	136603	A260	Conservation Crop Rotation
48	0.946	797491	A270	Conservation Cover Perennials
49	0.155	295557	A270	Conservation Crop Rotation
Total	**73.1323**	**6852259**		

Table A9 Climate change inputs to the HSPF model

Climate Change Level	Average Air Temperature Increase	Extreme Precipitation Percent Change
Mild	1 °F	4%
Moderate	2 °F	8%
Severe	4 °F	12%

Table A10 An expert's response towards selection of a suitable BMP for Mississippi corresponding to the 20 rules

Operator→ Criteria → Rule ↓	**IF Cost Effectiveness**	**AND Nitrogen Reduction Potential**	**AND Water Quality Improvement**	**AND Level of Acceptance**	**THEN Strategic Option**
1	Moderately High	Moderate	RRSP	CNHM	Depression Storage
2	Very High	Moderate Minus	FRNR	LMLI	Riparian Buffer
3	Moderate	Low	DNB	SFMC	Two-Stage Ditch
4	High	Very Low	SRNR	ACI	Riparian Buffer
5	Moderate	Moderate	SRNR	ACI	Depression Storage
6	Very High	Low	RRSP	LMLI	Saturated Buffer
7	High	Low	SRNR	ACI	Riparian Buffer
8	Moderately High	Very Low	FRNR	ACI	Saturated Buffer
9	Moderately High	Moderate Minus	FRNR	LMLI	Saturated Buffer
10	Moderate	Low	RRSP	CNHM	Riparian Buffer
11	Moderate	Low	DNB	LMLI	Depression Storage
12	Moderate	Moderate	FRNR	LMLI	Saturated Buffer
13	Very High	Low	FRNR	CNHM	Saturated Buffer
14	Very High	Low	SRNR	ACI	Saturated Buffer
15	Moderate	Moderate	SRNR	CNHM	Depression Storage
16	Moderately High	Moderate Minus	FRNR	CNHM	Saturated Buffer
17	Very High	Moderate Minus	SRNR	CNHM	Saturated Buffer
18	Very High	Low	SRNR	LMLI	Saturated Buffer
19	Moderate	Moderate Minus	SRNR	LMLI	Saturated Buffer
20	Moderate	Low	DNB	SFMC	Two-Stage Ditch

Table A11 Basic individual crops datasets for deriving crop rotation patterns water requirements and profit for Uttar Pradesh (India, 2022)

Crop	**Water Requirement (mm/per crop)**	**Production Cost (₹/ha)**	**Production (q/ha)**	**Cost Price (₹/ha)**	**Profit (₹/ha)**
Rice	575	41777	35.85	62738	20961
Wheat	550	36057	32	58880	22823
Maize	650	28553	22.93	38981	10428
Mustard	400	27539	11.74	49308	21769

Crop	Water Requirement (mm/per crop)	Production Cost (₹/ha)	Production (q/ha)	Cost Price (₹/ha)	Profit (₹/ha)
Potato	600	71311	186.01	148808	77497
Sugarcane	2000	56859	542.88	149292	92433
Sorghum	550	18630	11.5	31625	12995

Table A12 Computation of water requirements and profit related to crop rotation patterns for Muzaffarnagar (India, 2022)

Crop Rotation Patterns	Number of Cycles and Years for Completing Cropping Patterns in Whole Numbers	Water Requirement (mm/annum)	Profit/ha /annum (₹)
Rice-Wheat-Fallow	2 cycles / 3 years	750	29189
Maize-Wheat-Fallow	2 cycles / 3 years	800	22167.33
Maize-Potato-Maize-Wheat-Fallow	2 cycles / 5 years	980	48470.4
Maize-Mustard-Fallow	2 cycles / 3 years	700	21464.8
Sorghum-Mustard-Fallow	2 cycles / 3 years	633.33	66177.47
Sorghum-Wheat-Fallow	2 cycles / 3 years	733.33	23878.67
Rice-Mustard-Fallow	2 cycles / 3 years	650	28486.47
Rice-Wheat-Sugarcane-Fallow	Single cycle / 2 years	1562.5	68108.25
Maize-Wheat-Sugarcane-Fallow	Single cycle / 2 years	1600	62842
Rice-Potato-Sugarcane-Wheat-Fallow	2 cycles / 5 years	1490	85485.4
Rice-Mustard-Sugarcane-Wheat-Fallow	2 cycles / 5 years	1410	63194.28
Rice-Wheat-Sugarcane-Wheat-Fallow	2 cycles / 5 years	1470	63615.8
Rice-Potato-Maize-Potato-Fallow	2 cycles / 5 years	970	74553
Maize-Potato-Sugarcane-Fallow	Single cycle / 2 years	1625	90179

Table A13 Fundamental information for developing percentage annual average land use by individual crops under Maximization of Income Return scenario Muzaffarnagar (India, 2022)

Crop Rotation Practices for MIR	Number of Cycles and Years for Completing Cropping Patterns in Whole Numbers	Number of Cycles in Least Common Multiple Years of Practices (3*5*2 = 30)	Acreage (ha × 1000)
Sorghum-Wheat-Fallow	2 cycles 3 years	20	33.26
Rice-Potato-Sugarcane-Wheat-Fallow	2 cycles 5 years	12	28.51
Rice-Potato-Maize-Potato-Fallow	2 cycles 5 years	12	0.19
Maize-Potato-Sugarcane-Fallow	Single 2 years	15	154.22
NSP	------	------	44.53

Table A14 Percentage annual average land use by individual crops under Maximization of Income Return scenario for Muzaffarnagar (India, 2022)

Crops	Land covered by crops for MIR (ha)	Land covered by crops for MIR (%)
Rice	(12*28.51) + (12*0.19) = 344.4	2.655195
Wheat	(20*33.36) + (12*28.51) = 1007.32	7.766059
Maize	(12*0.19) + (15*154.22) = 2315.58	17.85225
Mustard	0	0
Potato	(12*28.51) + (24*0.19) + (15*154.22) = 2659.98	20.50745
Sugarcane	(12*28.51) + (15*154.22) = 2655.42	20.47229
Sorghum	(20*33.26) = 665.2	5.128442
Fallow	(20*33.26) + (12*28.51) + (12*0.19) + (15*154.22) = 3322.9	25.61831
Total	**12970.8**	**100**

Table A15 Information on the selected HRU and Subbasins corresponding to the study watershed in Chapter 4.

HRU	Subbasin	Area (km^2)
1	1	19.9381
2	1	110.388
3	1	12.3584
4	1	13.2415
5	1	17.17
6	1	17.4947
7	1	11.7015
8	1	12.3386
9	2	119.89
10	2	124.388
11	2	114.35
12	2	117.595
13	3	112.986
14	3	116.294
15	3	19.3693
16	3	111.756
17	4	19.2748
18	4	19.5872
19	4	16.6915
20	4	16.9169
21	5	114.126
22	5	113.038
23	5	110.191
24	5	19.4068
25	6	117.034
26	6	118.387
27	6	112.289
28	6	113.266
29	7	111.983

HRU	Subbasin	Area (km^2)
30	7	111.772
31	7	18.6454
32	7	18.4932
33	8	117.018
34	8	117.875
35	8	112.278
36	8	112.896
37	9	130.199
38	9	133.856
39	9	121.788
40	9	124.426

Table A16 Python Code

```
# Import packages
"""


import pandas as pd
import numpy as np
import matplotlib.pyplot as plt


"""# Load Data"""


# specify path to the file here
path = '/content/BNPs table.xlsx'
data = pd.read_excel('/content/BMPs table.xlsx')


# check the format of the data
data.head()


# Number of alternatives (BMPs) are read using data.shape[0]
SupMat = np.zeros((data.shape[0],data.shape[0]))
for row in range(data.shape[0]):  # iternating over rows
for col in range(data.shape[1]+1):  # iterating over cols
# using the formula from the paper to calculate network efficiencies
```

```
if row==col:
SupMat[row,col] = data.NitrateLoadReduction[row]/data.Cost[row]
else:
SupMat[row,col] = (data.NitrateLoadReduction[row]+data.NitrateLoadReduction[col])/(data.Cost[row]+data.Cost[col])
print(SupMat)


J =  np.ones_like(SupMat)
np.matmul(SupMat,J)


NormSupMat = np.divide(SupMat,np.matmul(SupMat,J))
print(NormSupMat)


"""# Stabilizing the Supermatrix to compute LimitMatrix"""
LimMat = np.linalg.matrix_power(NormSupMat,200)
print(LimMat)


"""# Saving efficiencies in the datafile"""
data.insert(data.shape[1],"Eff", LimMat[0,:], True)


"""# Selecting best $n$ BMPs"""
n = int(input('Enter value of n:'))
df1 = data.sort_values(by=['Eff'],ascending=False)
df1.BMP[0:n]


"""# Selecting 2nd best $n$ BMPs"""
df2 = df1.reset_index(drop=True)
df2.Eff[n-1] = 0
df2 = df2.sort_values(by=['Eff'],ascending=False)
df2.BMP[0:n]


"""# Selecting 3rd best $n$ BMPs"""
df3 = df1.reset_index(drop=True)
df3
df3.Eff[n-2] = 0
df3 = df3.sort_values(by=['Eff'],ascending=False)
df3.BMP[0:n]
```

AUX.2 Figures for analysis presentation

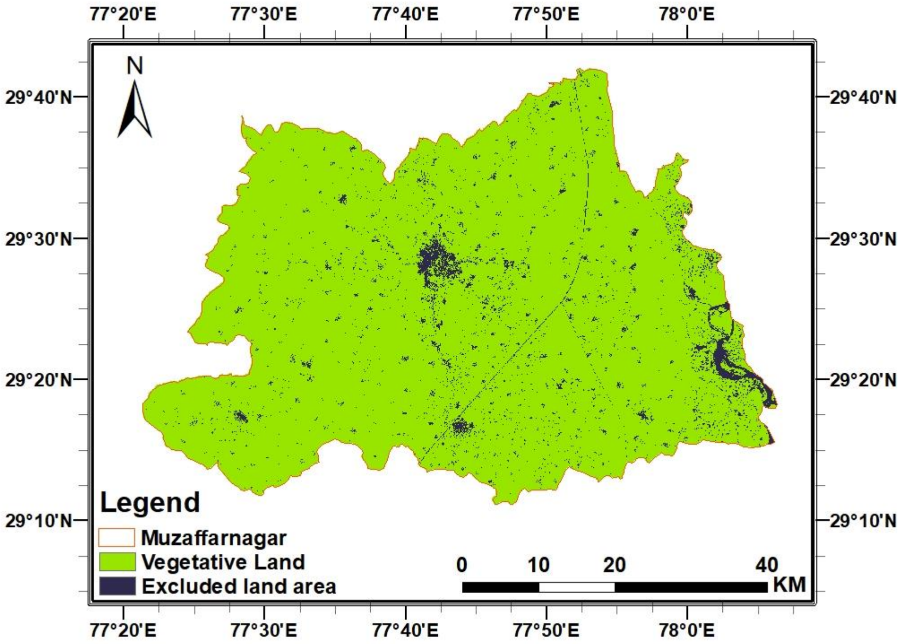

Fig. A1 Vegetative land use area for the Muzaffarnagar district (India) excluding built-up land, barren area, and waterbodies

APPENDIX-B

AUXILIARY INFORMATION TO THE RESEARCH ANALYSIS

B1. Ground Data Collection

Chapter 3:

- Consultation with the agronomy experts from ICAR, CPCB, Department of Irrigation and their qualitative opinions have been used to assign weightage to crop parameters.
- Collection of soil parameters for the 2700 soil sample points in the study watershed.

Chapter 4:

- The observed nitrate and discharge data collection for period 2010-2020 (both inclusive) the Central Water Commission, Ministry of Jal Shakti, Govt. of India, for the gauge station, Galeta.
- One-to-one questionnaire survey for 20 representative farmers in the study area.

Chapter 5:

- Interviews with a total of eight experts with distinct working experience, knowledge, and expertise, the stakeholders for taking their opinions regarding the probabilities of 21 basic events that might pose a challenge to adopting precision agriculture techniques.

Chapter 7:

- An expert panel consisting of fifteen stakeholders (i.e. Academicians and researchers - 6, Watershed planners - 4, and local farmers - 5) from the upper Mississippi watershed was consulted and a survey questionnaire was circulated to capture their judgments towards the selection of different strategic options under different possible scenarios.

B2. Questionnaires

Questionnaire B 2.1

Name of the Respondent:

Email ID of the Respondent:

How do you identify yourself?

A. Farmer
B. Agricultural Expert
C. Consumer
D. Academician or Scientist
E. Others (Please specify)

Do you feel that you can fit into one of these categories or if you are aware of the issues faced by one of these categories?

A. Innovators (Actively using different technologies and Active participation in farmer's meets and have installed mobile apps related to farming)
B. Early Adopters (Have some ideas of different technologies and are willing to implement new technologies)
C. Late Adopters (Apprehensive towards trying out new technology)

I. Innovators

What is the scale of the issues that you face with the cost of technology implementation of precision agriculture techniques?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

How much the precision agriculture techniques have increased your dependability on pesticides and chemicals?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

How much access do you have to the sustainability practices in agriculture anymore after implementing precision agriculture techniques?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

What is the scale of increase in energy consumption you feel that the operation of smart sensors and other gadgets has led to?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

How much increase did you experience with respect to the disposal of e-waste? (piles of discarded IoT tools and computers)

A. Very High
B. High
C. Medium
D. Low
E. Very Low

How much increase do you feel that the usage of precision agriculture techniques would lead to the loss of manual employment (replacement for on-farm manual labour)?

A. Very High
B. High

C. Medium
D. Low
E. Very Low

According to you, what is the scale of limitation of technology use (up to a certain extent you can implement the technology)?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

What according to you is the level of risk of malware and data thefts?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

According to you, what is the level of compatibility between different equipments and hardware devices?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

II. <u>Early Adopters</u>

What according to you is the level of financial support for the implementation of the precision agriculture techniques?

A. Very High
B. High
C. Medium
D. Low

E. Very Low

For small land holdings, what is the relevance of precision agriculture techniques?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

What do you feel is the scale of the current scenario of the installation/training assistance?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

What is the current level of regulatory and institutional policies that promote a national and international agenda for precision agriculture adoption?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

What is the scale of the scarcity of resources such as power supply and internet access?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

What do you think is the current status of the awareness of different technologies/lack of knowledge of controlling viruses and pests?

A. Very High

B. High
C. Medium
D. Low
E. Very Low

What is the ROI (Return on investment) on technology due to duration?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

III. Late Adopters

How rigid do you feel when it comes to adopting new technology?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

What is your level of dependency on traditional methods of farming?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

What is your level of reliance on weather conditions?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

How much is your level of resonance with the fact that the alternative technologies made precision agriculture adoption less attractive?

A. Very High
B. High
C. Medium
D. Low
E. Very Low

We would like to know any suggestions that you would like to propose to overcome the issues in the on-ground implementation of the precision agriculture techniques mentioned in the form.

What is the maximum benefit a farmer has derived from precision agriculture technology? (You can select multiple options)

A. Early crop disease detection
B. Optimal and timely usage of pesticides/fertilizers
C. Increase in production
D. Increase in market potential

According to your awareness, which shares of farmers in your territory are aware of the existence and potential advantages of precision agriculture techniques?

A. More than 75% of the farming community
B. Between 50-75% of the farming community
C. Between 25-50% of the farming community
D. The farming community is not aware

In your opinion, what factors influence farmers' adoption of precision agriculture techniques in your territory? (You can select multiple options)

A. Environment – climate reasons (e.g. less water pollution, improvement in soil structure, increase organic carbon in soils, less use of agricultural inputs etc.)

B. Efficiency gains (e.g. fewer production costs, less time spent, improves accuracy, better yields, reduced administrative burden etc.)

C. Improvement of labour conditions (e.g. better working conditions for farmers, reduced fatigue, possibility to work at dusk, dawn or night etc.)

D. Support to farming decisions through better data and information gathering
E. Introduction of innovative practices

In your opinion, are there any barriers to PAT adoption in your territory? (You can select multiple options)

A. Farmers are not aware of these technologies
B. Farmers are not interested in these technologies
C. The return on investment takes too long, the technology is too expensive
D. Farmers do not see the benefit of these technologies or find them too difficult to work with
E. Farms are too small
F. There are no contractors/dealers/companies offering such services in my territory
G. Bad/not sufficient internet connectivity

Are there any initiatives to improve internet connectivity in rural areas in your territory? (e.g. better broadband, dedicated measures in rural development programmes etc.)

A. Yes
B. No
C. I am not aware of any

Questionnaire B 2.2

Survey number________

Name:

Academic qualification:

Profession:

Experience:

Strategic options and Criteria are as presented below:

Strategic options	Criteria
S1: Depression storage (DS)	C1: Cost effectiveness (CE)
S2: Saturated buffers (SF)	C2: Nitrate reduction potential (NRP)
S3: Two-stage ditch (TSD)	C3: Water quality improvement (WQI)
S4: Riparian buffers (RB)	C4: Level of acceptance (LOA)

Goal: Assigning strategies suitable for the different combinations (in total 20) of classes under four criteria integrated using AND operator

Linguistic variables or the classes under "Cost effectiveness" criterion (Refer Fig. 7.3a)

VH-Very High *H-High* *MH-Moderately High* *M-Moderate*

Linguistic variables or the classes under "Nitrogen reduction potential" criterion (Refer Fig. 7.3b)

VL-Very Low *L-Low* *MM-Moderately Minus* *M-Moderate*

Linguistic variables or the classes under "Water quality improvement" criterion

RRSP- Runoff reduction and sediment pollution removal

FRNR- Flow reduction and Nitrogen removal (treat both surface and subsurface pollutants)

DNB- Denitrification and Biofiltration

SRNR- Slow down of runoff and Nitrogen Removal

Linguistic variables or the classes under "Level of acceptance" criterion

CNHM- Commonly perceived as nuisance and hard to maintain

LMLI- Requires little maintenance and low initial cost

SFMC- Has gained support from farmers, drainage managers, water conservation professionals

ACI- Acceptance with conflicts, incentives may be required

Please assign a strategic option with respect to each rule or a unique combination of criteria given below

Operator→ **Criteria →** **Rule ↓**	**IF** **Cost Effectiveness**	**AND** **Nitrogen Reduction Potential**	**AND** **Water Quality Improvement**	**AND** **Level of Acceptance**	**THEN** **Strategic Option**
1	Moderately High	Moderate	Moderately High	Moderate	---------
2	Very High	Moderate Minus	Very High	Moderate Minus	---------
3	Moderate	Low	Moderate	Low	---------
4	High	Very Low	High	Very Low	---------
5	Moderate	Moderate	Moderate	Moderate	---------
6	Very High	Low	Very High	Low	---------
7	High	Low	High	Low	---------
8	Moderately High	Very Low	Moderately High	Very Low	---------
9	Moderately High	Moderate Minus	Moderately High	Moderate Minus	---------
10	Moderate	Low	Moderate	Low	---------
11	Moderate	Low	Moderate	Low	---------
12	Moderate	Moderate	Moderate	Moderate	---------
13	Very High	Low	Very High	Low	---------
14	Very High	Low	Very High	Low	---------
15	Moderate	Moderate	Moderate	Moderate	---------
16	Moderately High	Moderate Minus	Moderately High	Moderate Minus	---------
17	Very High	Moderate Minus	Very High	Moderate Minus	---------
18	Very High	Low	Very High	Low	---------
19	Moderate	Moderate Minus	Moderate	Moderate Minus	---------
20	Moderate	Low	Moderate	Low	---------

Questionnaire B 2.3

Form No.: **Date:**

We are conducting a farmer survey in different sub-districts of Muzaffarnagar on the issues related to water conservation. The findings of this survey will be used for writing articles in journals of international prestige. This survey is an independent study and is not linked to any political party or government agency. Whatever information you provide will be kept strictly confidential. We hope that you will take part in this survey since your participation is important.

SECTION-1 (General information regarding farmer and the field)

1. Name:
2. Location/Address:
3. Contact (Mobile/Phone):
4. Age:
5. Education level (Tick one of the following):

○ Primary school (up to 10th standard) ○ Secondary/High school (11th to 12th) ○ University

6. Season-wise main crops grown in the field:

S.NO.	Major Crops Grown	Month of Sowing	Month of Harvesting
1			
2			
3			
4			
5			

7. The number of members in the family who participate in farming:

8. Source of irrigation and method of irrigation:

SECTION-2 (About Water Conservation)

1. **1.** Please tick one of the following options against each serial number given in the table (in red color)

Sr. No.	A good farmer is one who….	Not at all	Slightly	Somewhat	To good degree	Absolutely yes
1	… considers the health of waterways that run through or along his land as his responsibility	0	1	2	3	4
2	…minimizes soil erosion	0	1	2	3	4
3	…minimizes nutrient runoff into waterways	0	1	2	3	4
4	…thinks beyond his farm to the social and ecological health of the watershed	0	1	2	3	4
5	…maintains or increases soil organic matter	0	1	2	3	4
6	…manages for both profitability and minimization of environmental impact	0	1	2	3	4
7	…puts long-term conservation of farm resources before short-term profits	0	1	2	3	4

2. Please tick (multiple allowed) the water conservation practices you use or are planning to use in your field:

○ Tillage
○ Mulching
○ Field Bunding
○ Terracing
○ Nutrient Management
○ Strip Cropping
○ Retention Ditches
○ Nutrient Removal Wetlands
○ Riparian Buffers
○ Vegetative Barrier
○ Laser Land Levelling
○ Check Dams

3. Please mention any other conservation practice you use in your field but not mentioned above:

LIST OF PUBLICATIONS

1. **Aggarwal, S.**, Srinivas, R., Puppala, H. and Magner, J. 2022. Integrated decision support for promoting crop rotation based sustainable agricultural management using geoinformatics and stochastic optimization. *Computers and Electronics in Agriculture* 200, p. 107213. Available at: http://dx.doi.org/10.1016/j.compag.2022.107213.
2. **Aggarwal, S.**, Magner, J., Srinivas, R. and Sajith, G. 2022. Managing nitrate-nitrogen in the intensively drained upper Mississippi River Basin, USA under uncertainty: a perennial path forward. *Environmental Monitoring and Assessment* 194(10). Available at: http://dx.doi.org/10.1007/s10661-022-10401-4.
3. **Aggarwal, S.**, Srinivas, R., Magner, J., and Singh, A.P. Farmer adoption-based rapid networking for targeting optimal agro-conservation practices. *Environment Modelling & Software (Under Review)*.
4. **Aggarwal, S.**, Rallapalli, S., Nithyasree, T., Sabarish, B.A., Drewitz, M. and Magner, J. Decision support for cost-effective coalescence of agricultural conservation practices to meet total maximum daily loads in Pomme de Terre watershed. *Journal of Hydrology* (*Under Review).*
5. Pariartha, I.P.G.S., **Aggarwal, S.**, Rallapalli, S., Egodawatta, P., McGree, J. and Goonetilleke, A. 2023. Compounding effects of urbanization, climate change and sea-level rise on monetary projections of flood damage. *Journal of Hydrology* 620, p. 129535. Available at: http://dx.doi.org/10.1016/j.jhydrol.2023.129535.
6. Rallapalli, **S., Aggarwal**, S. and Singh, A.P. 2021. Detecting SARS-CoV-2 RNA prone clusters in a municipal wastewater network using fuzzy-Bayesian optimization model to facilitate wastewater-based epidemiology. *Science of The Total Environment* 778, p. 146294. Available at: http://dx.doi.org/10.1016/j.scitotenv.2021.146294.

BRIEF BIOGRAPHY OF CANDIDATE

SHUBHAM AGGARWAL

RESEARCH SCHOLAR
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Shubham Aggarwal is a Research Scholar in the Department of Civil Engineering, BITS-Pilani, Pilani Campus since November 2020. He obtained his M.E (Civil Engineering with specialization in Transportation Engineering) from Birla Institute of Technology and Science, Pilani in 2020, and his B.E Hons. (Civil Engineering) from the same Institute in 2018. Seeing his good performance in B.E. and M.E., he has been awarded two vertical transfers by BITS Pilani to the next level program. His research interests are Environment and Water resource planning and management, Mathematical modeling on water resources (both water quality and quantity assessment), Fuzzy logic application, Optimization techniques, and River basin planning. His primary professional goal is to become an expert in developing a conceptual framework of engineering, mathematics, and societal development, especially in context to water resources management. He has been developing several water quality models for restoration river Ganges in India and Mississippi River, USA for last 3 years.

Shubham has published 7 journal papers in high class journals of international repute such as Science of the Total Environment, Journal of Hydrology, Computer and Electronics in Agriculture, Environmental Monitoring and Assessment, Journal of Electronic Imaging, Construction and Building Materials, and Indian Concrete Journal. He has been awarded financial assistance (Merit-Cum-Need Scholarship) throughout his B.E. owing to his excellent academic performance. He has conducted and managed various cultural events as a Cultural Secretary for Punjabi Cultural Association, BITS Pilani. He also served as a volunteer in an English and Personality Development curriculum of National Service Scheme (NSS) – BITS Pilani. In addition, he has taught several courses of Civil Engineering such as Engineering Hydrology and Fluid Mechanics, Environment Impact Assessment.

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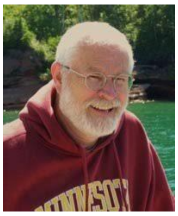
Dr. Rallapalli Srinivas is presently working as an Assistant Professor in the Department of Civil Engineering, BITS Pilani-Pilani Campus, Rajasthan (India). He is also serving as an Adjunct faculty at University of Minnesota (USA). His research interests are watershed modeling and simulation, environmental hydrology, hydro-climatology, and fuzzy logic-based decision making in water resources. Before joining BITS, he worked at University of Minnesota (UMN), U.S.A and successfully completed a project namely developing a field-scale optimized watershed modeling framework. He has also taught courses like Assessment and Diagnosis of Impaired Waters and Hydrology and Water Quality at UMN. In addition, he was nominated by UMN Water Resources Center to represent the university at Michigan Data Science Symposium in 2019. Dr. Srinivas is a member of Soil and Water Conservation Society (USA), American Society of Civil Engineers, and the Institution of Engineers. He is also a reviewer of leading journals such as Journal of Hydrology, Science of the Total Environment, Water Environment Research and Environmental Development and Sustainability. He has been invited to deliver keynote lectures at University of Michigan, University of Wisconsin, Iowa State University, National Resources Conservation Services (USA), Minnesota Association of Watershed Districts (USA) and Incessant Ganga Conference, Bihar Government (India).

He has published over 35 papers in journals and conferences of international repute. He has more than eight years of teaching and research experience in area of his expertise. Dr. Srinivas has also taught courses such as Engineering Hydrology, Water Resources Planning and Management, Multi-criteria Decision analysis in Engineering, Fundamentals of Systems Engineering, Water and Wastewater Treatment, and Surveying at BITS Pilani. He has also done significant work on water quality modeling and simulation of River Ganga during his Ph.D. titled as 'Multi-criteria decision analysis and modeling for water quality management in Ganga river basin'.



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Prof. Joe Magner has completed his B.S. in Soil and Water Science from University of Wisconsin in 1979 and Ph.D. in Hydrology and Watershed Management from University of Minnesota in 2006. His areas of interest are environmental and ecological engineering, exploring the ecological connection between increased precipitation and groundwater. And he has accomplished research in various domains including watershed assessment, management and policy, impaired waters and TMDLs, methods for exploring source waters, defining hydrologic pathways and processes using stable isotopes, ecological design of trap and treat systems, restoration of riparian zones and channels, and biophysical linkages and pollutant management with multi-stage ditches.

Prof. Magner is a licensed professional hydrologist (Wisconsin), a licensed professional soil scientist (Minnesota) and an American Institute of Hydrology registered professional hydrogeologist. He received degrees from the University of Wisconsin-River Falls and the University of Minnesota and has served as an environmental scientist and educator in varying roles for 42 years; primarily with the MN Pollution Control Agency but also advising US federal and local governments, and officials in China, India, Azerbaijan and South Africa. He teaches classes and advises students in water quality, hydrology, ecological engineering and watershed management. Joe has successfully advised over 40 graduate students along with 100+ publications. Joe is a co-author of the 4th edition of Hydrology and the Management of Watersheds published by Wiley-Blackwell (2013).