# CHAPTER 5

# DEVELOPMENT OF GROUNDWATER SUSTAINABILITY INDEX FOR HYPER ARID REGION OF RAJASTHAN, INDIA

In continuation with the previous chapter, this chapter specifically focused on the quantitative aspects of groundwater in the study area. The objectives of this chapter include: (i) to identify suitable indicators to assess groundwater sustainability; (ii) to develop a groundwater sustainability index; and (iii) to compute groundwater sustainability index for the study area.

## 5.1 INTRODUCTION

Sustainability has now been in use for a wide variety of activities such as project planning, development and establishments. Depending upon the user perspectives the necessity for sustainable development or sustainable utilization of resources may have rather different definitions. A system or process that is sustainable can last indefinitely.

Humanity has the ability to make sustainable development to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987). In this context, assuring the freshwater availability to cater the demand, human-health and well-being for people living in the ecosystem is among a major challenge (Damkjaer and Taylor, 2017). This challenge has been cherished in the United Nations Sustainable Development Goal (SDG 6.4) – "by 2030, substantially increase water-use efficiency across all sectors and reduce the number of people suffering from water scarcity" (UNSDG, 2015).

Such a system should be able to meet present freshwater needs without compromising the potential of future generations to accomplish their own water requirements. In general, a sustainable system is beneficial to the ecosystem, economy, social well-being, and equity. Water systems are dynamic, interlinked and complex, alike social water requirements. To accomplish sustainability in water use and water supply, managerial and administrative actions are essential to fit to the present and likely future state of natural and man-made water systems (Shilling et al. 2013). In order to make it possible, the managers and administrators should not only understand and acknowledge important aspects of natural and man-made water systems, but also ensure that these systems be operational within the domain as defined by community and nature.

Water sustainability answers are characterized by certain system properties, that may reflect total stability of the system. It is vital for sustainability that solutions to problems should be practical over a long time span. Also, the system should not face extreme changes in order to achieve desired solutions. The demand for freshwater is growing at fast pace due to growing population along with the aspirations of the community to be more prosperous and achieve high standards of living (Bartlett 1999, OECD 2018). On the other hand, the potential of the earth to meet these demands is decreasing at the same pace because of over-exploitation of groundwater, inefficient irrigation practices, incessant use of natural resources, and waste generation. Growing freshwater scarcity or inequitable availability of fresh and safe water can lead to severe health issues, poverty, and degradation of environment that in turn result into global hunger, civil unrest and conflicts. The only solution to these problems is to use natural resources sustainably (Flint, 2004a).

The framework of this study is intended to enable evaluation of development towards sustainability via a set of indicators, giving information about specific characteristics of groundwater systems in the region. Finally, a case study is conducted to demonstrate proposed methodology to assess groundwater (GW) sustainability in Bikaner district located in western Rajasthan, India. The region receives a very scanty rainfall throughout the year and comes under the hyper-arid zone. The prevailing condition of groundwater in the region is at its worst due to continuously falling water level, groundwater overdraft for domestic and agricultural irrigation purposes, along with low recharge rates as compared to very high extraction rates. The analysis carried out in this study will aid in developing suitable policy measures, continuous monitoring of groundwater resources, and setting appropriate targets to ensure its efficient uses. The outcome of the study will be in the form of a single score named as groundwater sustainability index (GSI). The literature studies addressing the groundwater sustainability and its assessment methodologies have been discussed in the Chapter 2 of this research work.

## 5.2 RESEARCH METHODOLOGY

The study has used a four step methodology to assess the groundwater sustainability of the arid region of western Rajasthan, India. Figure 5.1 depicts the graphical representation of the research methodology used for the study. The four steps of the research methodology are as follows:

- ✓ Planning –selection of suitable indicators and study area, scope of the study, and main objectives.

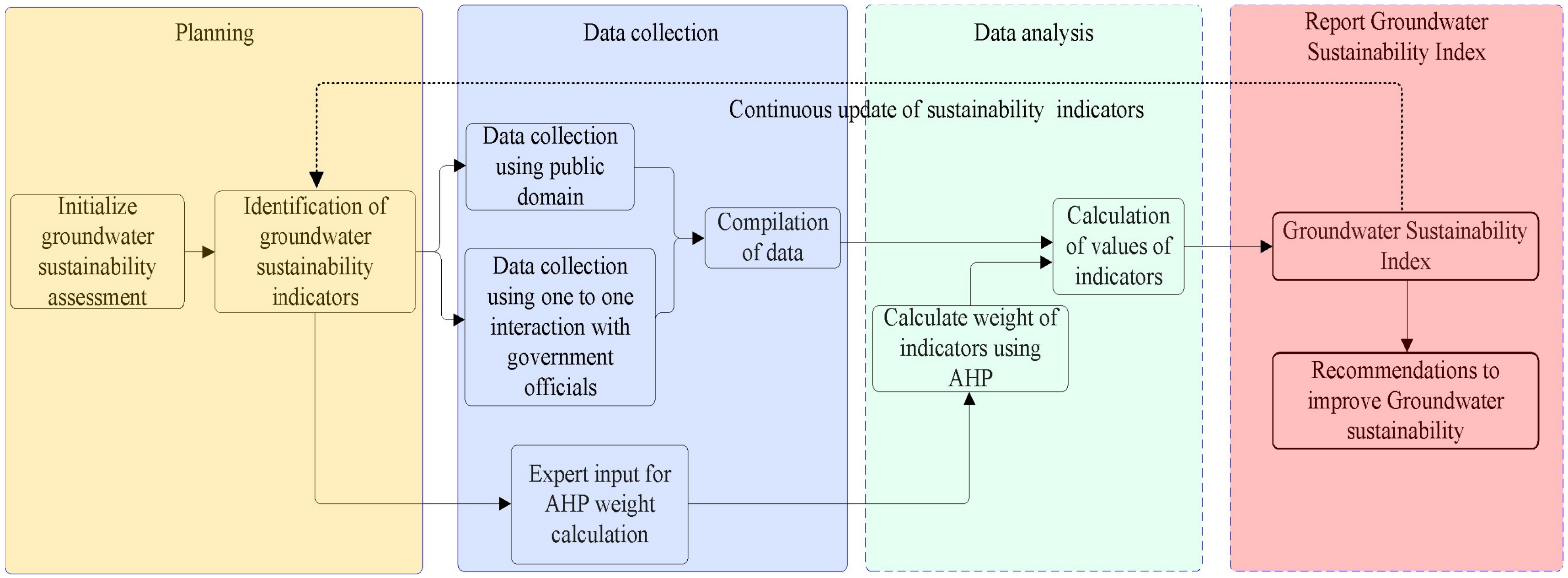


Figure 5.1. Research methodology used for the study

- ✓ Data collection – identification of reliable data sources, collection of data from literature and public domains, offline survey to collect relevant data from the expert/authorities engaged in the activities related to freshwater consumption; getting expert input for calculating analytical hierarchical process (AHP) weights of the selected indicators, and compilation of collected data.
- ✓ Data analysis – calculation of indicators values using the collected and complied data, and estimation of AHP weights for indicators and their dimensions.
- ✓ Reporting – interpretation of groundwater sustainability index (GSI) and suitable recommendations to the policy/decision makers for appropriate actions.

### 5.2.1 Selection of sustainability Assessment indicators

Indicators and metrics are key parameters for constitution of an index. Particularly for the developing economies, the selection of these indicators and metrics are really important. Commonly the indicators and metrics are selected using literature studies from previous work and also from the existing set of indicators and metrics. Groundwater sustainability indicators should address the social, economic, and environmental perspectives. A wide variety of indicators and their selection criterion are available in the existing literature studies. Liverman et al. (1988) suggested seven criteria for indicator selection. Juwana et al. (2012) also used the criteria suggested by Liverman et al. (1988). Veleva and Ellenbecker (2001) observed that there is a lack of guidance on how to choose among the suitable indicators. In this study, authors have considered similar selection criterion approach as proposed by Liverman et al. (1988) and Long et al. (2016), have also described salient points to choose appropriate indicators. The brief summary of groundwater dimensions along with selected list of indicators has been summarized in Table 5.1. These indicators have been used to derive sustainability index in the present study.

a) **Sensitive to change in time or reliable**: The indicator should be observable during a particular analysis period (time series). If the indicator is not reliable then it will lead to misleading information.

b) **Sensitive to change across space**: The indicator should be able to adopt the changes across groups or space. The indicator should be able to measure the useful information.

c) **Predictable:** An indicator should not only be able to predict or anticipate the signs of unsustainability but also be able to track the key factors causing unsustainability. Indicator of water stress consists of two components: availability of freshwater and population affected. Thus, the indicator can predict the availability of water if it is under menace (Falkenmark et al. 1989).

d) **Accessible with reference or threshold values:** In context of indicators assessing the sustainability, it is important to have indicators, which have some threshold values or reference values**.** Particularly in context of developing economies where availability of precise data is less probable, the issue of data availability has to be addressed properly.

e) **Appropriate and measurable:** First and foremost, important criteria for indicator selection is that it should be simple to measure and preferentially in quantitative forms. The indicator should also be efficient in converting raw data into meaningful values.

f) **Integrative and relevant:** The indicator should be able to provide signal to the decision makers in terms of relevant and meaningful information of the concerned issues. If the indicator can be integrated with other information, they should result effective decisions.

g) **Understandable and unbiased:** Biased indicators are developed commonly to support some particular motives. However, the development process of indicators itself include unavoidable bias because indicators are mostly chosen from existing indices or literature. It is important to develop indicators which are easy to interpret (for all stakeholders) and not biased due to some individual or political motives.

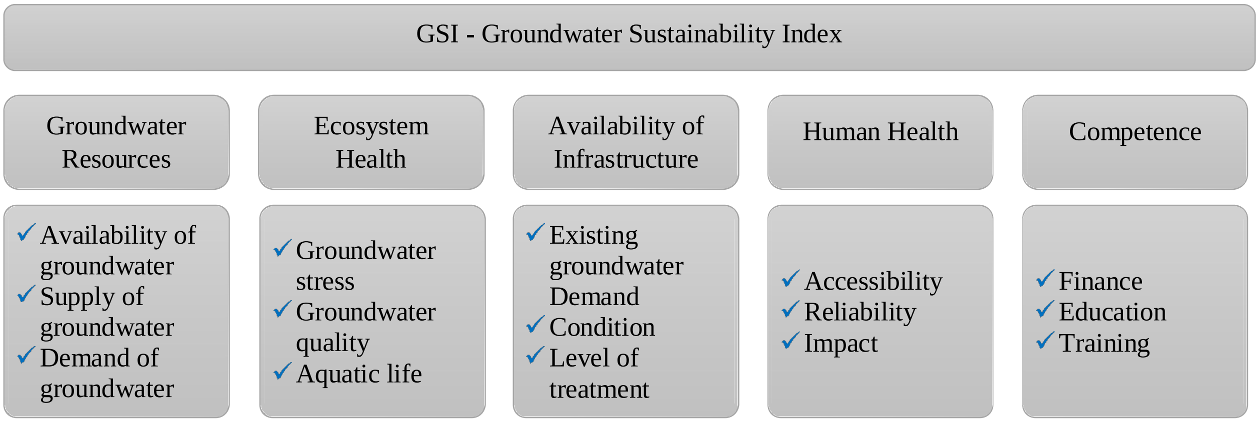
Table 5.1. Brief summary of selected indicators and their dimensions

| Groundwater sustainability dimensions | Indicators | Reference studies |
|---|---|---|
| Groundwater Resources | Availability of groundwater | Falkenmark et al. (1989); UNSD (2008); CWSI (2007); Bright et al. (1998); Vrba et al. (2007) |
| | Supply of groundwater | Gleick (1990); CWSI (2007); UNSD (2008); Raskin, (1997). |
| | Demand of groundwater | OECD 2004; UNSD (2008); CWSI (2007) |
| Health of ecosystem | Groundwater stress | UN, 1992; Gleick, 1996; CWSI (2007); Raskin, (1997); Vrba et al. (2007) |
| | Groundwater Quality | CWSI (2007); Dandautiya, et al.(2018); Gleick (1996); Ryder and Edwards, (1985); Singh et al. (2019); Srinivas et al. (2015); Summit E. UN (1992); UNSD (2008); Vrba et al. (2007) |
| | Aquatic life | CWSI (2007); Srinivas et al. (2018); Srinivas & Singh (2018) |
| Availability of infrastructure | Existing groundwater demand | UNSD (2008); CWSI (2007); Sullivan, 2002; OECD (2019); Bright et al. (1998) |
| | Infrastructure condition | Sullivan, (2002); Ivey et al. (2002); CWSI (2007); Bright et al. (1998) |
| | Level of treatment | UNSD (2008); Ofwat (2013); CWSI (2007); OECD (2018); Vrba et al. (2007) |
| Human health | Accessibility | Shiklomanov (1997); UNSD (2008); CWSI (2007); Holm, (2016); Sullivan, (2002) |
| | Reliability | Sullivan, (2002); Ofwat (2013); CWSI (2007); |
| | Impact | UNSD (2008); Dawe (1990); OECD (2018); CWSI (2007) |
| Competence | Finance | de Loe et al. (2002); Shanaghan et al., (1998); CWSI (2007) |
| | Education | US EPA, (1998); CWSI (2007); Shanaghan et al., (1998) |
| | Training | US EPA, (1998); CWSI (2007); Ivey et al. (2002) |

Indicators can translate the sustainability related challenges or freshwater related issues in quantifiable measures. Therefore, indicators are powerful tool to support effective decision making, raise awareness, provide meaningful information, and trace the progress towards defined targets. The proposed indicators are based on existing literature studies and indices addressing the water sustainability in different regions of the globe. The study has taken special care to take into account the geological and climatic conditions of the study area.

### 5.2.2 Defining the Dimensions and Indicators of the Groundwater Sustainability Index (GSI)

The study uses five dimensions addressing the groundwater resources sustainability using a concise list of 15 indicators, derived on the basis of parameters important for water sustainability. The data required and its collection process for all of the 15 indicators is discussed in the description of the indicators. Figure 5.2 shows the selected groundwater sustainability indicators.



GW – Groundwater

Figure 5.2. Selected groundwater sustainability assessment dimensions and indicators

### 5.2.3 Groundwater Resources

The groundwater resource component is estimated by using the scale of groundwater and endowment of available groundwater, so that the resource can meet the demand of specific population reliably. It is evident to mention here that the study might use the words groundwater and freshwater interchangeably, as this study considered only groundwater as a source of freshwater in the study area. Therefore, the assessment is carried out on all the relevant indicators. In this dimension three indicators are selected to quantify the groundwater resources – availability of groundwater; supply of groundwater; and demand of groundwater. The first indicator is oriented to assess the total availability of renewable groundwater resources. The variability in the water supply is measured using supply of groundwater indicator and demand of groundwater indicator assesses the present level of demand for freshwater.

#### 5.2.3.1 Availability of Groundwater

The indicator is aimed to evaluate the annual availability of renewable groundwater in terms of $m^3$ per capita per year. On the basis of population demand of the study area and the amount of groundwater extracted the value of indicator can be obtained. The widely acceptable indicator of Falkenmark water stress is utilized for benchmarking the minimum quantity required to meet economic, ecosystem, and domestic needs.

Falkenmark et al. (1989) states that an amount of 1700 $m^3$ per capita per year is enough to meet the necessary water requirements of the population; whereas an amount less than 1700 $m^3$ per capita per year might create issues in terms of economic, reliability, and basic needs as shown below:

> 1700 nearly no water shortage

1000 – 1700 Water shortage appears on regular basis

500 – 1000 Water shortage is limited towards human health, well-being, and economic development

< 500 Availability of freshwater is main restraint to life.

As per the above values, the availability of 1700 $m^3$ per capita per year is given a score of 100 and value of 500 per capita per year is given a score of 0. The value lying between 1700 and 500 can be estimated using the equation (5.1). So, the value of availability of groundwater indicator ($G_A$) can be computed as:

$$G_A = \frac{T_{cap} - 100}{(1700 - 500)} \times 100 \tag{5.1}$$

where: $T_{cap}$ = available renewable groundwater (in $m^3$ per capita per year),

If $T_{cap} > 1700$, then $G_A = 100$,

If $T_{cap} < 500$, then $G_A = 0$.

### 5.2.3.2 Supply of Groundwater

The indicator of supply of groundwater is aimed to visualize the variability or trend in the groundwater reserves. The indicator can also be named as 'variation in water supply system'. High variations in the groundwater reserve may result in serious implication of water supply for both domestic and economic use. The indicator can also be used to indicate the population vulnerability towards natural calamity like drought or flood.

The groundwater supply indicator ($S_{GW}$) is estimated using the trend in water level in the regional wells. The water level also reflects through the fluctuation in water table. The groundwater department of state of Rajasthan, India carry out the pre-monsoon and post-monsoon survey for assessing the change in water level. It is observed that the wells exhibit three situations – 1) rise in the water level, 2) no change, and 3) decline in water level. To estimate the value of groundwater supply indicator, the study provided the score of 1 – rise in water level, 0.5 - no change, and 0 – decline in water level. To estimate the indicator value equation (5.2) is used as follows:

$$S_{GW} = (r + 0.5n) \times 100 \tag{5.2}$$

where: r = % of wells with rising water levels,

n = % of wells with no change in water level.

### 5.2.3.3 Demand of Groundwater

The indicator values are obtained on the basis of total groundwater draft against the net availability of renewable groundwater throughout the year. The groundwater (GW) draft against the multiple uses has been defined in terms of domestic, irrigation, industrial, and municipal. The high GW demand is associated with the implications related to its sustainable use. The amount of GW draft is the maximum water available for use but the amount of withdrawal is not the amount utilized. To estimate the demand of groundwater indicator ($G_D$), following equation (5.3) is used:

$$G_D = \left(1 - \frac{d}{T}\right) \times 100 \tag{5.3}$$

where: d = amount of groundwater draft ($m^3$/year)

T = total renewable groundwater resources ($m^3$/year)

If $d/T \geq 1$, then $G_D = 0$.

### 5.2.4 Ecosystem Health

The indicator is selected to assess the qualitative analysis of the groundwater resources. The ecosystem health dimension is oriented to assess the pressure imposed on the ecosystem in terms of groundwater stress. The second indicator selected to assess the ecosystem health is groundwater quality – which is deterioration of quality due to excessive withdrawal.

#### 5.2.4.1 Groundwater Stress

The indicator purposed to assess the pressure imposed on the ecosystem. The ecosystem might get effected due to excessive use of water withdrawal. The indicator value is calculated using annual water consumed relative to renewable groundwater resources available annually. It is assumed that 60 percent of renewable groundwater is required to sustain a healthy and functional system. Therefore, the score of groundwater stress ($G_S$) can be computed on the basis that a groundwater consumption rate with a value of 40% or above is given a score of 0 as shown below in equation (5.4):

$$G_s = \frac{0.4 - \frac{c}{T_{GW}}}{0.4} \times 100 \tag{5.4}$$

where: c = annual amount of water consumed ($m^3$/year)

$T_{GW}$ = total annual renewable groundwater availability ($m^3$/year)

If $c/T_{GW} > 0.4$, then $G_S = 0$

If $c/T_{GW} = 0$, then $G_S = 100$

If $0.4 > c/T_{GW} > 0$, then the above equation should be used to get score of groundwater stress ($G_S$).

The indicator has a low specific relevance towards the health of ecosystem but it has quite broader uses towards sustainable use of water.

### 5.2.4.2 Groundwater Quality

The indicator is selected to assess the deterioration of quality due to excessive withdrawal and use. The parameters affecting the deterioration of water quality are metals, nutrients, ions, organic materials, and physical impurities. On the basis of their values, the water quality index score can be calculated. To measure these data, a continuous monitoring of different sites of groundwater availability or extraction is essential. When the value of water quality index (WQI) is very poor then indicator score has been assigned as 0, whereas a value of 100 has been assigned for excellent quality of water.

For the estimation of WQI, field values were compared with the standard values as prescribed in BIS (2012) and Batabyal and Chakraborty (2015). Data for a total of 12 parameters, addressing the groundwater quality in the region is obtained from groundwater department of the region. The parameters are – Electrical conductivity (EC), total dissolved solids (TDS), pH, sodium, potassium, calcium, magnesium, chloride, sulphate, fluoride, and total hardness. The range for quality are chosen as index value: WQI <50 – excellent quality; 50 <WQI <100 – good, 100<WQI<200 – poor; 200 < WQI < 300 – very poor; WQI > 300 – not suitable for drinking. The average WQI value for the region is estimated as 246.5 (very poor quality). So, the value of this indicator is 0.

### 5.2.4.3 Aquatic Life

This indicator mainly performs a reality check to understand whether the ecosystem process is being negotiated by anthropogenic and/or natural instabilities. The indicator outlines various parameters such as water flow, quality and quantity which in turn reports about the physical and chemical status of the water resource.

The present study carried out in the desert/arid region of India and mainly focused on the groundwater sustainability assessment. There is no data available for the assessment of aquatic life corresponding to this study area.

### 5.2.5 Availability of Infrastructure

The infrastructure dimension of the groundwater resource sustainability addresses both the state of wastewater and freshwater. In this dimension, three indicators are chosen – existing demand of infrastructure, the existing conditions of the available infrastructure to cater the need of the society, and level of treatment the existing infrastructure can provide.

#### 5.2.5.1 Existing Groundwater demand

The capability of existing groundwater infrastructure in terms of freshwater supply and its treatment is assessed using this indicator. The indicator is defined as – the time period required to reach the infrastructure system up to its full 100% capability (referred as $T_{100}$). If the demand changes with the time, it can drive the infrastructure to update with new facility or system upgradation. The equation (5.5) is utilized to estimate the infrastructure demand:

$$T_{100} = \frac{\log FP - \log CP}{\log(1+P_r)} \tag{5.5}$$

where: FP = the population that can be served when the system is at 100% capacity assuming a constant consumption of water per person along with incorporating the trend adjustments

CP = population currently served by the system

$P_r$ = population growth annually.

The value of $T_{100}$ for both freshwater and wastewater infrastructure is estimated. It is assumed that when there is a negative population growth, the value of existing groundwater infrastructure ($I_D$) should be assigned as 100. But, if there is an increase in population, the value for $T_{100}$ can lie between 50 and 100. This means that the system can take 50 or more than 50 years to reach the full capacity, then the score for $I_D$ can be assigned as 100. If the infrastructure is already on its full capacity, then the value of $I_D$ can be taken as 0. To calculate the score of $I_D$, equation (5.6) has been used.

$$I_D = \frac{T_{100}}{50} \times 100 \tag{5.6}$$

If $T_{100}$ is 50, then value of $I_D$ will be - 100

If $T_{100}$ =100, then value of $I_D$ will be - 0

If $0 < T_{100} < 50$, these use equation (6) to estimate the $I_D$ value.

Though the score for groundwater infrastructure ($I_D$) has been estimated for both freshwater and wastewater, the lowest score is used for the index value estimation.

#### 5.2.5.2 Infrastructure Condition

The indicator majorly addresses the system loss in percentage for both the freshwater and wastewater infrastructure systems. The indicator not only visualizes the inefficiencies but also provides aid for repair issue identifications. It can also provide an idea that if there is any leakage or losses, to what extent it is affecting the environment. Equation (5.7) is useful to estimate the losses and scoring the infrastructure condition ($I_c$) by assuming that 25% or more losses are assigned score of 0 and 0% losses are assigned score of 100. The value of loss lying in-between can be estimated as follows:

$$I_c = 100 - \left(\frac{l}{25} \times 100\right) \tag{5.7}$$

where: $l$ = losses in percentage

value of $l \geq 25$, then $I_c = 0$

value of $l = 0$, then $I_c = 100$.

Initially, score for infrastructure condition ($I_c$) has been estimated for both freshwater and wastewater. The lowest score has been considered for the index calculations.

### 5.2.5.3 Treatment

This indicator is mainly focused on treatment of wastewater. The assessment is based on the level of treatment of wastewater facilitated before its release from the plant. The three levels of treatment are taken into consideration: primary treatment, secondary treatment, and tertiary treatment. Only suspended impurities are removed in primary treatment, whereas in secondary treatment suspended and dissolved biological impurities are being removed. In the tertiary treatment, suspended, biological, chemical and nutrients contaminations are being removed.

The population served through municipal sewers is taken into consideration to assess the wastewater treatment level. The factors scoring are considered as follows – for no treatment, factor is 0; primary treatment, factor is 1/3; secondary treatment, factor is 2/3; tertiary treatment, factor is 1. Individuals using their own septic tanks or associated with sewer services are not included. The secondary treatment also includes the sewage lagoons and waste stabilizing ponds. The equation (5.8) is used for estimation of level of treatment ($I_T$)

$$I_T = \left(\frac{1}{3}p + \frac{2}{3}s + t_e\right) \times 100 \tag{5.8}$$

where: $p$ = percentage of population served by primary treatment facility sewer

$s$ = percentage of population served by secondary treatment facility sewer

$t_e$ = percentage of population served by tertiary treatment facility sewer.

### 5.2.6 Human Health

This component deals with the three major concerns related to human health viz., potable drinking water accessibility, reliability of the groundwater supply and the impact of available fresh and potable groundwater on the residents of the community.

#### 5.2.6.1 Accessibility

Shiklomanov (1997) suggested that, 150-250 lpcd of water is required to fulfil demands like drinking, bathing, cleansing. In order to assess the indicator value, the total amount of fresh and potable groundwater available is compared with the number provided by Shiklomanov (1997). So, if a community earns a value of at least 150 lpcd, a score of 100 has been assigned, and conversely, if it earns a score of 50 lpcd or below, it has been assigned a score of zero. The indicator value ($H_A$) can be computed using the below given equation (5.9).

$$H_A = 100 - \left(\frac{150-y}{150-50} \times 100\right) \tag{5.9}$$

where: y = quantity of potable water accessible to per person per day (in litres per capita per day)

$H_A$ value = 100 when y = 150

$H_A$ value = 0 when y = 50

When 50 < y < 150, then use equation (9).

Basically, this indicator deals with the amount of fresh and potable groundwater available to a community in terms of per person per day.

### 5.2.6.2 Reliability

Situations like poor infrastructure and various other disruptions make the supply system of groundwater unreliable. So, this indicator evaluates the reliability of the groundwater supply by analyzing the total service failure periods in days throughout the year.

In order to evaluate the value of this indicator, the total number of service interruption in days per year are computed per person. The total number of service interruption days per person per year are computed using equation (5.10):

$$S_{DD} = \frac{\sum_{i=1}^{N}(P_i - d_i)}{\mathrm{T}_{pop}} \tag{5.10}$$

where: $S_{DD}$ = total service disruption days accounted in per capita,

N = Total no. of disruption occurred in a year,

$P_i$ = estimated population affected due to disruption of service,

$d_i$ = total duration of service disruption in day *i*,

$T_{pop}$ = total population.

The maximum number of service interruption days can be taken as 365. The indicator value ($H_R$) can be computed using equation (5.11) as given below:

$$H_R = \left(1 - \frac{S_{DD}}{365}\right)^3 \times 100 \tag{5.11}$$

In order to ensure that service interruption days' value is not rewarded, the provision of cubing the inverse percent has been introduced as shown in equation (11).

### 5.2.6.3 Impact

This indicator reports the groundwater quality, quantity and the resulting impacts on human health. Diseases which are generally caused due to water i.e. waterborne diseases such as cholera, diarrhoea, escherichia coli are very common in India. In order to assess the impact on human health due to these waterborne diseases and to compute the indicator value ($H_I$), total number of illness cases per 1000 people is used in the below equation (5.12).

$$H_I = (1 - w) \times 100 \tag{5.12}$$

where: $w$ = number of sickness/illness cased reported due to waterborne disease per thousand population

$H_I$ value = 100 when $w = 0$,

$H_I$ value = 0 when $w \geq 1$.

A value equal to 100 refers that there are no cases of illness due to waterborne diseases and a value equal to zero refers that one or more illness cases are there per 1000 people.

### 5.2.7 Competence

This indicator deals with the capability of a community on the basis of three key parameters as financial capability, educational capability, and number of personnel trained to effectively manage the water resources. The vitality of the component is reflected as it highlights the social and economic aspects of the resources available to the society.

#### 5.2.7.1 Finance

The indicator is evaluated when surplus revenues over expenditure is observed in relation with the national minimum and maximum level. For example, if local government of Mizoram is having highest per capita surplus and Haryana is having highest debt. Now these minimum and maximum values are used as a benchmark to compute the value for financial indicator ($C_F$), as shown in equation (5.13).

$$C_F = 100 - \left(\frac{F_{max} - s}{F_{max} - F_{min}} \times 100\right) \tag{5.13}$$

where: $F_{min}$ = the state with minimum surplus money per capita

$F_{max}$ = the state with maximum surplus money per capita

$s$ = surplus money per capita for the study region.

#### 5.2.7.2 Education

The indicator value is computed based on the level of education in the society. The more the people are educated, more skills they have, which will essentially lead to approach for a practical and technical solution against any problem or crisis locally and serve the community in a better way. If the individuals are educated, then they will also be careful about their health and the environment. This indicator is important and contributing for the development of groundwater sustainability index because education inculcates various skills and capabilities in individuals to manage their water resources effectively and efficiently in a more sustainable way.

The score of the indicator ($C_E$) is computed based on the percentage of population under the age group 18-50 who have earned senior secondary level qualification. As per the Census 2011, the Kota district in Rajasthan has maximum percentage of population of about 76.56 % with at least senior secondary qualification, whereas Jalore district of Rajasthan has minimum with about 54.86 %. The availability of educated people in the state of Rajasthan with minimum and maximum percentages have been considered as a benchmark to compute the score of the education indicator ($C_E$) using equation (5.14).

$$C_E = 100 - \left(\frac{E_{max} - e}{E_{max} - E_{min}} \times 100\right) \tag{5.14}$$

where: $E_{max}$ = region with maximum % of population having at least senior secondary level education

$E_{min}$ = region with minimum % of population having at least senior secondary level education

$e$ = % of population of the study area having senior secondary level qualification

$C_E = 100$, If $e = 76.56\%$

$C_E = 0$, If $e = 54.86\%$

If $54.86\% < e < 76.56\%$, then equation (5.14) has been used.

#### 5.2.7.3 Training

This indicator reflects the society's capability in terms of handling their freshwater resources after empowering them with basic training about handling and management of the water resources. In order to generate a score for the indicator ($P_{TV}$) the percent of people trained and empowered has been calculated and multiplied by a factor for various sectors as shown in equation (5.15).

Industrial training = 1

Some other training = 0.5

Not trained = 0

$$P_{TV} = (n + 0.5t) \times 100 \tag{5.15}$$

where: n = % of people empowered with new industrial skills

t = % of people gone through some other training.

## 5.3 GROUNDWATER SUSTAINABLE INDEX (GSI) COMPUTATION

At first stage, the computed indicator scores are used to compute the overall score at dimension level by averaging the two or three indicators constituting a particular component. This in turn estimates the final index value (GSI) for a given area of interest using equation (5.16).

$$GSI = \frac{\sum_{i=1}^{N} w_i X_i}{\sum_{i=1}^{N} w_i} \tag{5.16}$$

where: $X_i$ refers to indicator *i* of the index for the selected dimension

$w_i$ = global weight of the selected indicator.

For the purpose of internal assessment as per the requirements of a community, weighing of any dimension can be attuned accordingly.

### 5.3.1 Data Collection and Analysis

#### 5.3.1.1 Analytical Hierarchical Process

Aanalytic hierarchy process (AHP) was introduced by Saaty (1980). AHP is a philosophy of estimation, which offers the capability to include both quantitative and qualitative features in the decision making process. It can also aid the decision method by individual or organizational perspective, personal emotions, memories, and judgments within a hierarchic structure consisting of various levels, which then influence the decision making. The process of analytical hierarchy starts with the development of a structured problem in a hierarchical form. After development of hierarchical structure, the elements are evaluated by decision makers in pairwise comparisons. Further, in AHP pairwise comparison matrixes are generated by stating a single number between 1-9 or verbal judgements like: high, medium, and low, on the basis of preferences or relative importance of two elements in relation to the above level elements.

In the present study, analytical hierarchy process (AHP) has been used for determining the weights of selected dimensions of groundwater resource sustainability. The expert opinions used for study are from, academic expert working in the area and government official (hydrogeologist and other relevant designations) working in the department of groundwater, Government of Rajasthan, India and Central Ground Water Board, Government of India. To obtain the weightage input on the selected dimensions, one to one interaction is carried out with the officials. The AHP process is defined in the following five steps:

STEP I. First define the scales of comparison as given in the Table 5.2.

Table 5.2: Definition of Saaty Scale

| Saaty Scale | Definition |
|---|---|
| 1 | Equally important (E. Imp.) |
| 3 | Weakly important (W. Imp.) |
| 5 | Fairly important (F. Imp.) |
| 7 | Strongly important (S. Imp.) |
| 9 | Absolutely important (A. Imp.) |
| 2 | The intermittent values between two adjacent scales |
| 4 | |
| 6 | |
| 8 | |

The decision makers make a pair-wise comparison of indicators based on Saaty scale. In terms of linguistic variables, e.g. if the decisive authority states “criteria 1 (C1) is weakly important over criteria 2 (C2)”, then it takes 3 as the value according to the corresponding numbers whereas in the pairwise contribution matrix of these criteria, the comparison between C2 to C1 will take the value ‘1/3’.

STEP II. If there are more than one decision maker, preference of each, $(\widetilde{d_{ij}^{k}})$ are averaged and $(\widetilde{d_{ij}})$ is calculated as shown in equation (5.17)

$$\widetilde{d_{ij}} = \frac{\sum_{k=1}^{K} \widetilde{d_{ij}^{k}}}{K} \tag{5.17}$$

STEP III. According to averaged preference, pairwise contribution matrix is modernized as shown in equation (5.18)

$$\check{A} = \begin{bmatrix} \widetilde{d_{11}} & \cdots & \widetilde{d_{1n}} \\ \vdots & \ddots & \vdots \\ \widetilde{d_{n1}} & \cdots & \widetilde{d_{nn}} \end{bmatrix} \tag{5.18}$$

The pair wise comparison matrix for the five dimensions selected for the groundwater resources sustainability is shown in Table 5.3.

Table 5.3. Pair wise comparison matrix for dimensions

| Dimensions | Groundwater resource | Health of ecosystem | Availability of infrastructure | Human health | Competence |
|---|---|---|---|---|---|
| **Groundwater resource** | 1.00 | 3.00 | 5.00 | 5.00 | 1.00 |
| **Health of ecosystem** | 0.33 | 1.00 | 3.00 | 5.00 | 0.33 |
| **Availability of infrastructure** | 0.20 | 0.33 | 1.00 | 3.00 | 0.14 |
| **Human health** | 0.20 | 0.20 | 0.33 | 1.00 | 0.14 |
| **Competence** | 1.00 | 3.00 | 7.00 | 7.00 | 1.00 |

STEP IV. The geometric mean of comparison values of each criterion is calculated.

STEP V. The fuzzy weights of each criterion are estimated by using the equation (5.19) and weights are shown in Table 5.4.

$$\widetilde{w_i} = \widetilde{r_i} \big/ (\widetilde{r_1} + \widetilde{r_2} + \cdots + \widetilde{r_n}) \tag{5.19}$$

Here, $\widetilde{r_i}$ represents triangular values.

Table 5.4. Weights obtained for the dimensions

| Dimensions | Weights |
|---|---|
| **Groundwater Resources** | 0.3380 |
| **Health of ecosystem** | 0.1607 |
| **Availability of infrastructure** | 0.0752 |
| **Human health** | 0.0445 |
| **Competence** | 0.3816 |

#### 5.3.1.2 Data Collection for Various Indicators Under the Five Dimensions

The primary data for the selected indicators are collected from various national and state level reports and publications on water resources. Few data are also obtained from financial reports and publications from the state and national government. The secondary data for the indicators are collected through personal visits and discussion with groundwater department officials of the State of Rajasthan of Bikaner district. The data collected is converted into relevant form to estimate the values of indicators and ultimately to evaluate the dimension scores. The major reports and documentation are: Census of India (2011); Groundwater Year Book, 2016-17; TERI, (2017); UNEP, (2012); CGWB, (2013); Service Level Benchmarking Gazette Notification, 2018-19; Study on Planning of Water Resources of Rajasthan, (2014); and Urban Rajasthan Opportunities and Septage, (2017).

### 5.3.2 Groundwater Sustainability Index and Reporting

On the basis of data collected for the 15 indicators and AHP weights obtained, the groundwater sustainability index (GSI) of the Bikaner region is computed. The values of individual indicators, dimension scores, and the final GSI score are provided in Table 5.5.

The groundwater resource dimension with a value of 20, related to three indicators *viz.* availability of groundwater, supply of groundwater, demand of groundwater was analysed. If the indicator – availability of groundwater obtains a score of 100, it means adequate amount of freshwater is available to the community for their basic water needs. In our case the indicator scored 19.67, which refers to a critical situation and there is a need to focus on the availability of groundwater in the region. Secondly, the indicator – supply of groundwater reflects vulnerability of freshwater supply system with a score 39.5. At last the indicator – demand of groundwater obtained a score of zero due to groundwater overdraft is prevalent in the region.

Table 5.5. Groundwater sustainability index calculation

| Groundwater sustainability dimensions | Dimension weights | Indicators | Indicator values | Dimension score (average of indicator scores in each dimension) | Groundwater sustainability index (using eq. 5.16) |
|---|---|---|---|---|---|
| **Groundwater Resources** | 0.3380 | Availability of groundwater | 19.67 | **20** | **21** |
| | | Supply of groundwater | 39.5 | | |
| | | Demand of groundwater | 0 | | |
| **Health of ecosystem** | 0.1607 | Groundwater stress | 0 | **0** | |
| | | Groundwater quality | 0 | | |
| | | Aquatic life | No Data | | |
| **Availability of infrastructure** | 0.0752 | Existing groundwater demand | 0.25 | **8** | |
| | | Condition | 8 | | |
| | | Level of treatment | 13.67 | | |
| **Human health** | 0.0445 | Accessibility | 20 | **59** | |
| | | Reliability | No data | | |
| | | Impact | 97 | | |
| **Competence** | 0.3816 | Finance | 5.27 | **28** | |
| | | Education | 50.69 | | |
| | | Training | No data | | |

The health of ecosystem dimension obtained a score of zero due to the indicators getting either negative or zero score. The stress indicator secured a negative value because stress on the groundwater system is maximum due to high consumption rate of community in the region. The groundwater quality indicator is based on water quality index.

The average water quality index value of the region comes under very poor category and thus the indicator obtained a score of zero. Aquatic life indicator score has not been obtained due to non- availability of data for the region. The infrastructure dimension with a value of 8 and the indicator value of 0.25 for existing groundwater demand, represents that the available infrastructure is almost running at its 100% capacity.

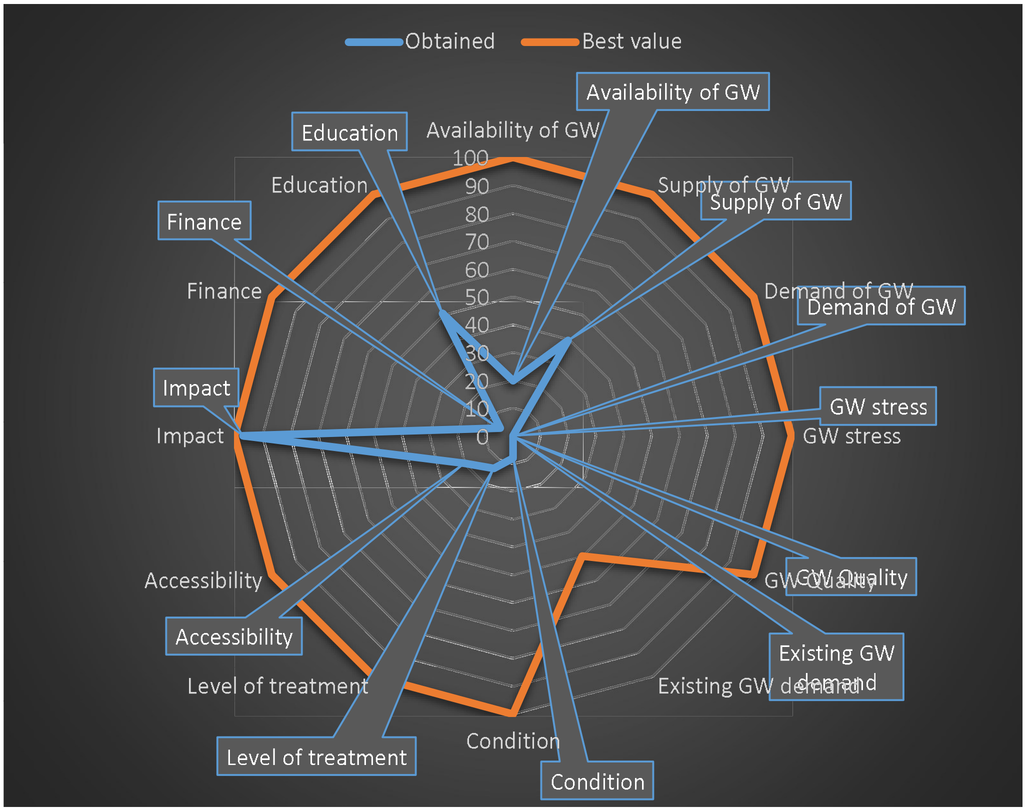


Figure 5.3. The radar chart showing the performance of indicators

With the existing growth rate of population, the infrastructure needs to be updated with immediate effect. The condition indicator, with a value of 8, refers to some high losses in the supply system. The treatment indicator also visualizes the worst condition with a score of 13.67, which means most of the population do not have access to the treatment facilities in context wastewater treatment and reuse. The only dimension where the region scores comparatively better was the human health with a score of 59. The major reason behind the comparative high score was less number of illness cases due to waterborne diseases. The high score of health indicator is basically an outcome of very low rates of disease in the area which is due to under-reporting of water borne disease cases as was confirmed by the medical personnel concerned with the data center. There could have been various reasons for under-reporting as if patient is a bit educated, he/she can go for self-treatment, sometimes people take it casually when they suffer from water borne illnesses. There could be some diagnostic issues and human error while registering the water borne cases. The value of competence dimension is moderately lower than the human health dimension. It is observed that level of education in the community is better, whereas in terms of finance there is a need for policy reformation in order to support capacity building and to improve the situation of financial deficit per capita.  Figure 5.3 depicts comparative analysis for all selected indicators in terms of their estimated performance scores with respect to required/best performance. The estimated performance of indicators in the study represents a highly unsustainable behavior of the groundwater management. It can be observed from the Figure 5.3, that only impact indicator is found close to the required/best value whereas the remaining indicators need to be addressed very carefully in order to sustain the human life and provide safe and healthy freshwater to meet their needs.

## 5.4 QUALITATIVE ASPECTS OF GROUNDWATER SUSTAINABILITY

Beside the above discussed quantitative indicators, there are many qualitative indicators which have direct impact on the groundwater resource sustainability. Two qualitative aspects are discussed in this section due to their contemporary importance – ‘effect of urbanization on groundwater or vice-versa’ and ‘effect of climate change on groundwater resources’.

### 5.4.1 Effect of Urbanization on Groundwater or Vice-versa

Urban population of the world is predicted to reach almost 70% by 2050, which will impose serious challenges among the government to provide healthy and quality life to the citizens (Shen et al. 2011). This will directly impact the natural resources sustainability such as groundwater, both in terms of quantity and quality. These socio-environmental impacts on the inhabitants, and water resource management in urban area has become vital, complicated and challenging for the governing bodies (Kalhor and Emaminejad, 2019). There are tools available to predict and assess the level of urbanization or human settlements in the different regions of the world such as European Commission’s Global Human Settlement Framework. The tool used in this framework assess a large amount of spatial data to predict the human settlement in different regions of the world (European Commission, 2019). Researchers use different approaches to assess the impact of urbanization on water resources (Kumar et al. 2019, Kalhor and Emaminejad, 2019). These efforts and tools analyze a large number of spatial data but it is not possible to develop quantitative relation between urbanization and its impact on groundwater resources. As per the world factbook published by the Central Intelligence Agency of US, 34% of Indian population currently live in urban areas with an annual urbanization rate of 2.37% (CIA, 2019). Whereas, the level of urbanization in the study area between 1991-2001 was 2.76%, which was reduced to 2.55% between 2001-2011 (Government of India, 2019). Keeping in view of its importance, such study can be considered as the future scope of the study, so that shifts in socio-economic transitions can be understood across different parts of the world with specific reference to these parameters.

### 5.4.2 Effect of Climate Change on Groundwater Resources

Both the direct and indirect effect of climate change on groundwater are more complex over the surface water, as the human settlement in the groundwater dependent regions vary from days to thousand years. The changes in climatic conditions not only impact the groundwater recharge and flood/drought, but also the human demands (Gurdak, 2017). The impact of human settlement and climate change in the study region is visible from the rate of increased groundwater pumping. This can be understood from the statistics provided by the Central Ground Water Board on the stage of groundwater development in the study area, which ranges from 132.48% in 2013 to 170.28% in 2017 (CGWB, 2013; CGWB, 2017). Asoka et al. (2017) provided the scientific verification of above statement by estimating the groundwater depletion rate of 2 cm/year (minimum) in the study area. Further, climate change and its impact on the earth behavior can be studied mainly through three types of models: simple climate models–assessing the energy balance; earth system model with intermediate complexity level; and global climate model (Green et al., 2011). Assessing the temperature depth profile of tube wells is also a parameter to assess the impact of climate change, as it represents the temperature history and recharge. The study region commonly consists of deep bore wells, and in case of deep aquifers, water levels are subjected to annual or long-term climate variabilities as compare to shallow aquifers (Asoka et al., 2017). Another aspect of climate change variability on groundwater is that sustainability of water supplies is not only dependent on the quantity but also on the quality and other factors such as hydrogeology of region, groundwater policies, and socio-economic aspects (Reilly et al., 2008). The impact of climate change on groundwater depends upon the following parameters – soil and aquifer combinations, crop rotations, vegetation, and climatic conditions (Green et al., 2011). As suggested by Gurdak (2017), discrimination between human induced or climate induced groundwater variability is difficult. Developing an indicator for measuring the impact of climate change on groundwater in the region (Groundwater sustainability index perspective) has been found complicated and hence only descriptive literature has been provided in the present study. Although the study has extensively covered various aspects of groundwater stress, which have also been influenced due to climate change variabilities, it has been revealed through detailed discussions with the experts from state groundwater department that in the current situation, it is difficult to define a quantitative indicator of groundwater sustainability with minimum and maximum threshold values of climate change variabilities for the study area. This is due to the unavailability of reliable and trustworthy data on climate change variabilities and its impact on groundwater in the region. It is also believed that assessing the impact of climate change on groundwater has great potential as the future scope of the research because no existing study has been undertaken the issue to visualize this impact in quantitative terms, and farmers are still dependent on the groundwater supplies for irrigation and domestic purposes.

## 5.5 SUMMARY

The work presented in this chapter is oriented to provide a single score groundwater sustainability index (GSI) for the Bikaner district of Rajasthan. The GSI provides a clear visualization of groundwater resource sustainability to various stakeholders in the region. To develop the GSI, literature review and an AHP methodology were utilized. The literature studies, existing indices, state and national level reports and other publications are used to identify the suitable indicators. The secondary data for the indicators and inputs for AHP process are obtained from experts working in the field of groundwater resources. On the basis of collected data, the values of each indicator, dimensions, and the GSI are computed. It is observed that the overall sustainability of groundwater resources in the region is very poor. In terms of the five dimensions, health of ecosystem and available infrastructure for the sustainable management of groundwater secured a very low score. This clearly indicates that the situation is more than alarming and governing bodies should take necessary actions immediately, if the groundwater demand of the community has to be catered securely. The human health dimension performance was found better as compared to groundwater resources and competence required. It is also observed that analyzing the results by individual indicators can support the improvement initiatives. The indicators need to be updated from time to time for the inclusion of new benchmark and to assess current situation of groundwater. The GSI can be used for training, planning, awareness, and also as an education tool in the region, for the sustainable management of groundwater. The continuous monitoring/assessment of groundwater in the study area, which is a water scarce region, will be the key for governing bodies. The present approach can be easily implemented in the other regions or communities by modifying the indicator weights as per the prevailing conditions.

Although the study has extensively covered the aspect of groundwater stress, which has been influenced due to climate change variabilities, it has been revealed from detailed discussions with experts from state groundwater department that in the current situation, it is difficult to define a quantitative indicator of groundwater sustainability with minimum and maximum threshold values of climate change variabilities for the study area. This is due to the unavailability of reliable and trustworthy data on climate change variabilities and its impact on groundwater in the region. It is also believed that assessing the impact of climate change on groundwater has great potential as the future scope of the research because no existing studies has undertaken the issue to visualize this impact in quantitative terms, and farmers are still dependent on the groundwater supplies for irrigation and domestic purposes. Similarly, urbanization impact studies on groundwater can be performed by developing quantitative relation between urbanization and its impact on groundwater resources which could not be done due to lack of data for the case study under present scenario. Keeping in view of its importance, such study should be taken as the future scope of the study so that shifts in socioeconomic transitions can be understood with specific reference to these parameters across different parts of the world, especially in developing country like India.

# CHAPTER 6

# LIFE CYCLE ASSESSMENT OF GROUNDWATER SUPPLY SYSTEM IN A HYPER-ARID REGION OF INDIA

## 6.1 INTRODUCTION

Water is one of the most important resources for sustaining all forms of life by fulfilling basic needs and health. The demand for freshwater use to meet the daily needs grew twice as fast as the world's population. The major thrust behind this was 70% of global water withdrawal for agricultural purposes (Berger et al., 2016; Finkbeiner, 2016). The over exploitation of freshwater bodies including groundwater may create a situation of freshwater crisis for future generations especially in Asia and Africa (Koehler, 2008). In many regions of India, the groundwater replenishment is dependent upon rainfall. It is observed that in the last decades the rainfall is scanty and not sufficient to replenish the levels of groundwater extracted during non-monsoonal times (Srinivas et al., 2015). The second important aspect of ground water is its extraction, which is mainly done using electricity. According to Gilron (2014), the connection between energy and water is quite complicated, as generation of electricity also demands for high water consumption (Gilron, 2014). In Indian context, 59.9% of the total electricity is generated using coal based thermal power plants (CEA India, 2014). This makes the situation of water energy nexus more complicated for extraction of ground water in the hyper arid regions of India, where ground water is the only source of freshwater and energy is generated using coal based power plants. The environmental impacts associated with the consumption of water are often neglected, especially with regard to agricultural production that happens in water scarce areas (Berger et al., 2016; Finkbeiner, 2016). Hence, management of water resources in the arid and hyper arid zones is essential.

Life Cycle Assessment (LCA) is a commonly used environmental management tool for assessing environmental consequences throughout the product life cycle. However, in the existing research for LCA of products or processes, attention is provided only for pollution of freshwater resources by various categories. The tool of LCA is mainly emerged in developed economies and availability of freshwater varies at various locations around the globe, which makes it challenging for the impact assessment of water use with different water qualities (Finkbeiner, 2016). In case of arid countries (for example India, Australia, Spain) and water intensive crops, impact of water used can be the main contributor to overall food production impacts (Dijkman and Basset-mens, 2018).

The current study aims to visualize the potential environmental impacts of groundwater supply system for irrigation purpose using LCA. The study area (i.e. Bikaner block) under consideration falls under hyper arid zone category in the Thar Desert of India. In this region, most of the irrigation systems rely on groundwater supply, which is extracted from deep bored tube wells using submersible pumping system. In this study, environmental impact assessment of groundwater extraction from tube wells and its use for agricultural purpose has been performed. The system boundary of the study consists of well construction (WC), groundwater extraction (GWE), distribution (D), and end-of-life (EoL). The data for the study has been collected through semi-structured interviews conducted with the farmers, equipment dealers, and authorities of district electricity board. The actual measurement of material and energy consumption have also been done to validate the data.

## 6.2 LCA AND WATER RESOURCE MANAGEMENT

The boundary of LCA begins with raw material extraction and ends when all materials are returned to the earth. LCA is a tool used for qualitative and quantitative assessment of environmental hazards and life cycle costing of product, process or value chain (Klöpffer, 1997).

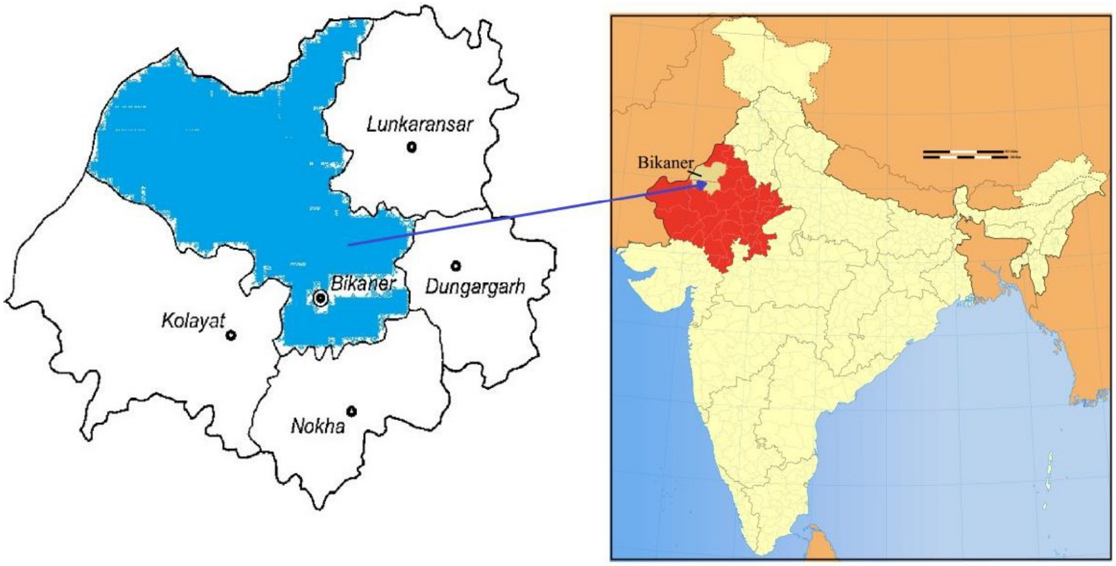


Figure 6.1. Map showing location Bikaner district and five blocks of the district

LCA has been widely used nowadays for various products and processes (Bhakar et al., 2015), but this is yet not popular in the field of freshwater resource management, especially in India. Many researchers around the world have focused on application of life cycle management tools to assess freshwater resources and their overall impact upon environment, socio-economic aspects, and vice versa. Koehler (2008) highlighted the critical aspects of water use in LCA and also pointed out the issue of water scarcity in Asia, particularly in India and China. According to Bayer et al. (2009), LCA of groundwater extraction is a potential research topic.

It stated that LCA as a tool needs further consideration beyond its industrial applications. Boulay et al. (2011) focused on categorizing the type of water and water users for LCA inventory. The study categorized two types of agricultural water users: one is good quality irrigation water user and another is relatively poor-quality water user. Milà et al. (2009) focused on assessment of freshwater use impacts, development of inventory model, and characterization factors for impact assessment. A few studies have applied LCA in agricultural sector. Birkved and Hauschild (2006) used LCA to estimate the environmental impacts due to use of pesticide in agricultural and illustrated the capability of the model through two real time Danish case studies. Dijkman et al. (2012) also focused on impacts related to use of pesticides in agricultural sector in Europe. In this sequence, few studies have been conducted in the context of water footprint assessments in India. Bhakar et al. (2015) focused on assessing the environmental impacts associated with water supply system of a university campus. Another study by Bhakar et al. (2016) focused on treatment and purification of freshwater supplied to the residents of a university campus for drinking purposes. Ghazi et al. (2008) evaluated the environmental impacts associated with the mud generated in drilling operations.

## 6.3 GEOGRAPHICAL LOCATION OF THE STUDY AREA

Bikaner is located in the north-western part of the state of Rajasthan and has international border with Pakistan. It has an area of 30381.75 sq. km. It lies between 27° 11' and 29° 03' north latitudes and 71° 54' and 74° 12' east longitudes. The district is having five blocks/panchayat samities viz. Bikaner, Kolayat, Lunkaransar, Sri Dungargarh, and Nokha. The location of study area is shown in Figure 6.1. The climate of the Bikaner block ranges from arid in the east to extremely arid/hyper arid in the west and is characterized by large extremes of temperature, erratic rainfall and high evaporation. Being situated on the western side of Aravalli hill ranges, the area is characterized as typical rain shadow region resulting in low precipitation. The average annual rainfall of the block is 262.11 mm for the last eleven decades. High temperature here starts from April onwards whereas May and June are the hottest months of the year. From April to June, temperature exceeds 40.0°C generally whereas in some years' temperature has been recorded above 47.0°C. With the onset of monsoon in late June or early July, the daytime temperature falls to 38.0°C in July to 36.0°C in August and September.

## 6.4 MATERIALS AND METHODS

In this study, environmental impacts associated with one kilolitre of groundwater extracted for agricultural purposes have been assessed using LCA. The LCA is carried out using ISO 14040 framework (ISO, 1997). This framework consists of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 1997). This study utilizes a cradle to grave approach to model the material and energy flows. The life cycle environmental impact assessment of ground water extraction can visualize the hotspots and might be helpful in decision making for groundwater extraction. In this study, Umberto NXT Universal software and Ecoinvent dataset version 3.0 (Swiss Centre for Life Cycle Inventories, 2015) are used to model the energy and material flow. The well-known ReCiPe impact assessment method is utilized for both endpoint and midpoint assessment. The impacts generated due to extraction of one kilolitre of groundwater are plotted against various impact categories and interpretations have been drawn based on potential impact assessed corresponding to each category.

## 6.5 GOAL AND SCOPE DEFINITION

### 6.5.1 Functional Unit

In the present study, the functional unit has been considered as one cubic meter of groundwater (freshwater) distributed for irrigation purposes from a tube well using submersible pump.

### 6.5.2 System Boundary

The system boundary of the study includes the construction of tube wells (including rotary drilling operation, pipe lowering, gravel packing, and submersible pump installation), groundwater extraction, distribution using sprinkler system, and disposal of the material after useful life. The system boundary of the study has been shown in Figure 6.2.

### 6.5.3 Inventory Analysis

The inventory analysis of the study has been carried out using both primary and secondary data. For primary data collection, semi structured interviews were conducted among various stakeholders dealing with various aspects of groundwater management. The primary data includes water usages, pump operation hours, load capacity of the submersible pump, usage of sprinkler systems, etc. The list of stakeholders includes farmers, equipment dealers, and authorities from electricity board.

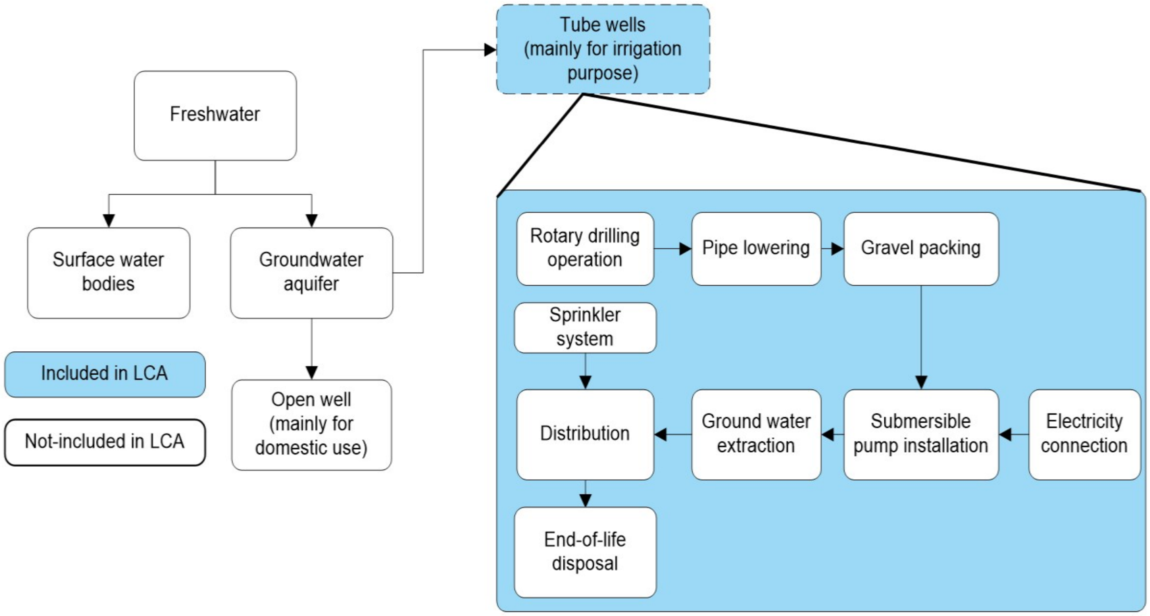


Figure 6.2. System boundary of the study

In total 58 stakeholders were interviewed, out of which 44 interviewees were farmers, 6 were equipment dealers, and 8 were from electricity board authorities of the district. The average semi-structured interview lasted about 25-30 minutes each. The energy consumption data have been collected by actual measurement and it was verified with the information provided by authorities of district electricity board. The secondary data for the study are collected through available online literature and equipment brochures. The energy consumption data is taken from billed usage of the consumers. Finally, the primary and secondary data were combined together to conduct the inventory analysis. The Ecoinvent datasets are used for modelling the energy and material flow model. Production and market activities from global dataset are used to model the data for well construction and, the data for Indian electricity mix has been considered to model the energy consumption for ground water extraction phase, and global dataset from Ecoinvent v3.0 database are used for distribution and end-of-life treatment phases. The functional unit of the study has been considered as 1 m$^3$ of groundwater (freshwater) extracted for irrigation purpose. The present study has carefully incorporated the life of equipment and materials, and their share in the extraction and distribution of groundwater, as shown in Table 6.1. The basic material and energy flow model of the study is shown in Figure 6.3.

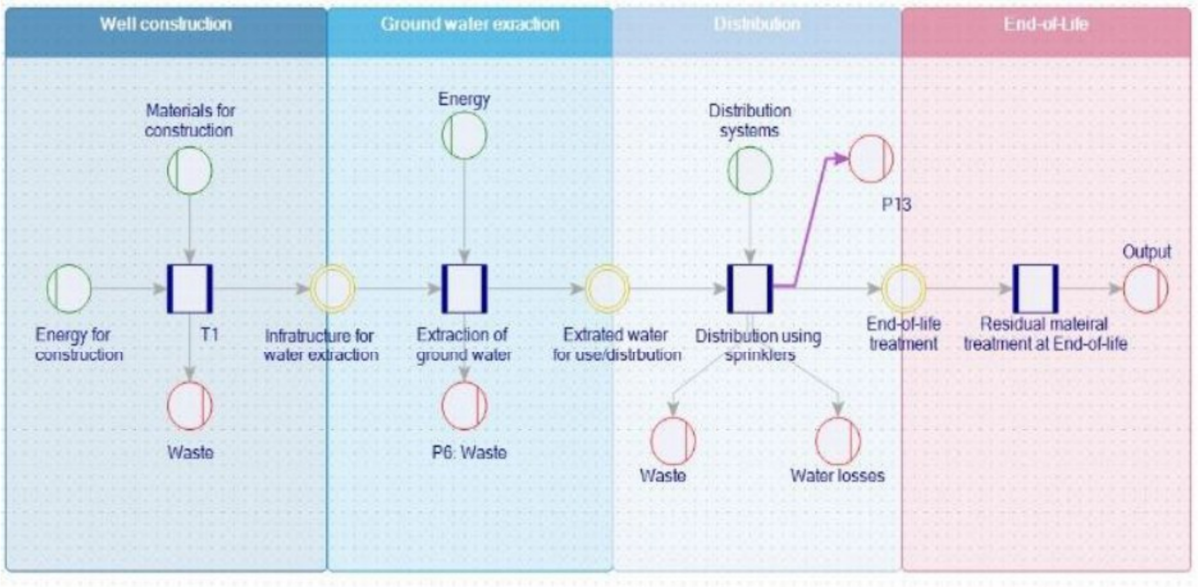


Figure 6.3. Basic material and energy flow model of the study

Table 6.1. List of main inventory analysis data used to model

| S. No. | Product | Material | Quantity | Quantity for 1 $m^3$ water | Life in years |
|---|---|---|---|---|---|
| 1 | Pipe for well | Asbestos | 37 Pipe/well | 1.51 Kg | 10 |
| 2 | Packing for pipes in well | Gravel (1680 kg/m3) | 62160 Kg/well | 15.5 Kg | 10 |
| 3 | Electric Cable | Plastic | 246 gm per meter | 0.025 Kg | 5 |
|  |  | Copper | 164 gm per meter | 0.015 Kg | 5 |
| 4 | Transportation | Transport lorry 3.5-7.5 | 600 Metric ton*km | 0.15 Metric ton*km | - |
| 5 | Submersible Pump | Copper | 15.44 Kg/pump | 0.004 Kg | 5 |
|  |  | Plastic insulation | 1.56 Kg/pump | 0.0004 Kg | 5 |
|  |  | Steel | 135 Kg/pump | 0.034 Kg | 5 |
| 6 | Water | Withdrawal | 22.17 $m^3$/hr | 1 $m^3$ | - |
| 7 | Sprinkler system | Nozzle | 420 gm each | 0.0015 Kg | 5 |

| | | | | | |
|---|---|---|---|---|---|
| | | Foot button | 100 gm each | 0.0004 Kg | 5 |
| | | GI Pipe + clip | 960 gm per meter | 0.0034 Kg | 5 |
| | | HDPE Pipe | 6 kg per 20 feet length | 0.0986 Kgs | 5 |

GI = Galvanized iron, PVC = Polyvinyl chloride,

The above data is taken for a 40 HP submersible pump used to discharge 900 LPM water, upto a maximum height of 600 feet. Initially the data for well construction is collected for one well and the energy consumption data has been measured for random sample wells and verified afterwards with records of 687 wells from district electricity authority. It is assumed that each of the tube well runs for 6 hours in a day for 30 days, with an average discharge of 22.17 $m^3$/hr of groundwater. Hence, the total water withdrawal from the 687 tube wells in a month is estimated around 2741540 $m^3$. The LCA model has been developed for one cubic meter of water withdrawal (as shown in Table 6.1).

## 6.6 IMPACT ASSESSMENT

The well-known ReCiPe method has been utilized to perform the impact assessment (Huijbregts et al., 2016). Both midpoint and endpoint assessment have been carried out using ReCiPe method. In midpoint assessment nine categories are considered for assessment – climate change (CC – kg $CO_2$-Eq), fossil depletion potential (FDP – kg oil-Eq), freshwater ecotoxicity potential (FETP – kg 1,4-DCB Eq), human toxicity potential (HTP – kg 1,4 - DCB Eq), metal depletion potential (MDP – kg Fe-Eq), natural land transformation (NLT – $m^2$), ozone depletion potential (ODP – kg CFC-11 Eq), particulate matter formation (PMF – kg $PM_{10}$-Eq), and water depletion potential (WDP – $m^3$). Endpoint assessment results have been analysed under three categories: ecosystem quality, human health, and resources.

### 6.6.1 Midpoint Assessment Results

The midpoint assessment results have been analysed in this section.

#### 6.6.1.1 Phase-wise Analysis

In phase-wise analysis, it is observed that the End-of-Life (EoL) phase has negligible impact on all the categories of midpoint assessment. The well construction (WC) phase has been found to have the highest impact, followed by ground water extraction (GWE), and distribution (D) phase. In well construction phase, the most significant factors for environmental impacts are packing of well, and consumption of copper, steel and fossil fuel. The energy consumed during extraction process is significantly affecting the environment in all the given categories. The phase-wise distribution of impact assessment is shown in Figure 6.4.

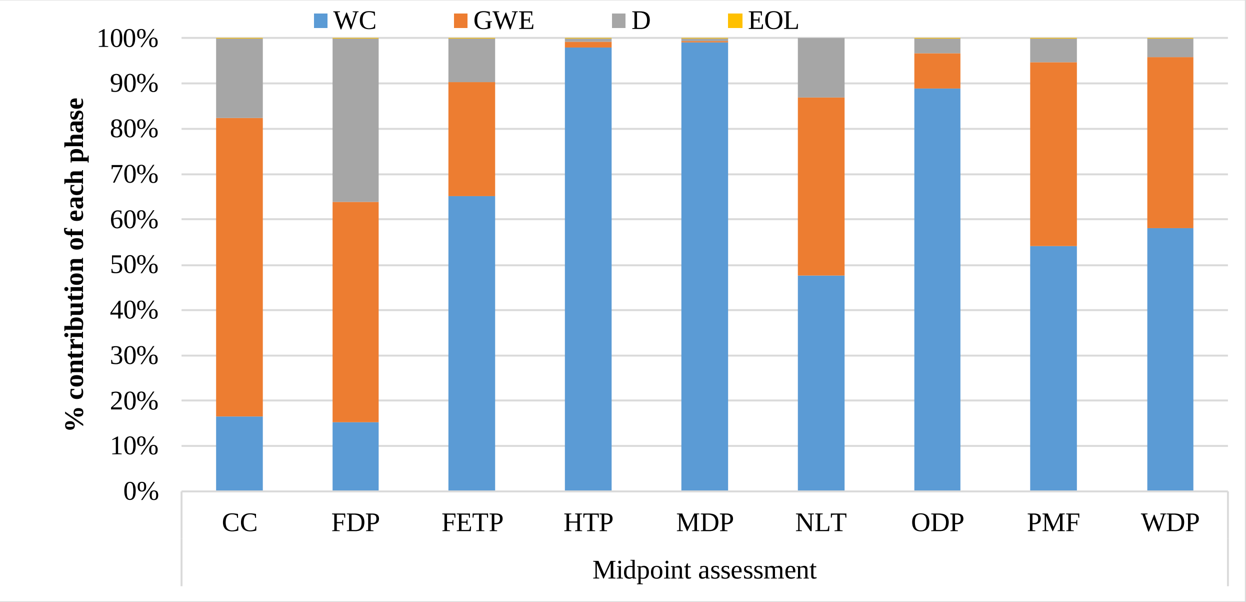


Figure 6.4. Phase-wise analysis of midpoint assessment

### 6.6.1.2 Categorical Analysis

It has been observed that the consumption of copper (used in submersible pump) has high impact during the entire extraction process under almost all the categories followed by distribution systems, and energy consumed in process of water extraction as described in Figure 6.5. After analysis, it is found that the toxic heavy metals used for copper processing are arsenic, cadmium, selenium, manganese, zinc, etc. are mainly responsible for the environmental impacts generated. Further the present study is compared with the findings of similar studies. Godskesen et al. (2018) used LCA to report that 0.00019 Kg $CO_2$ eq. is emitted for obtaining one liter of drinking water. The present study estimates the carbon footprint for one liter of groundwater in Indian context to be 0.00775 Kg $CO_2$ eq.

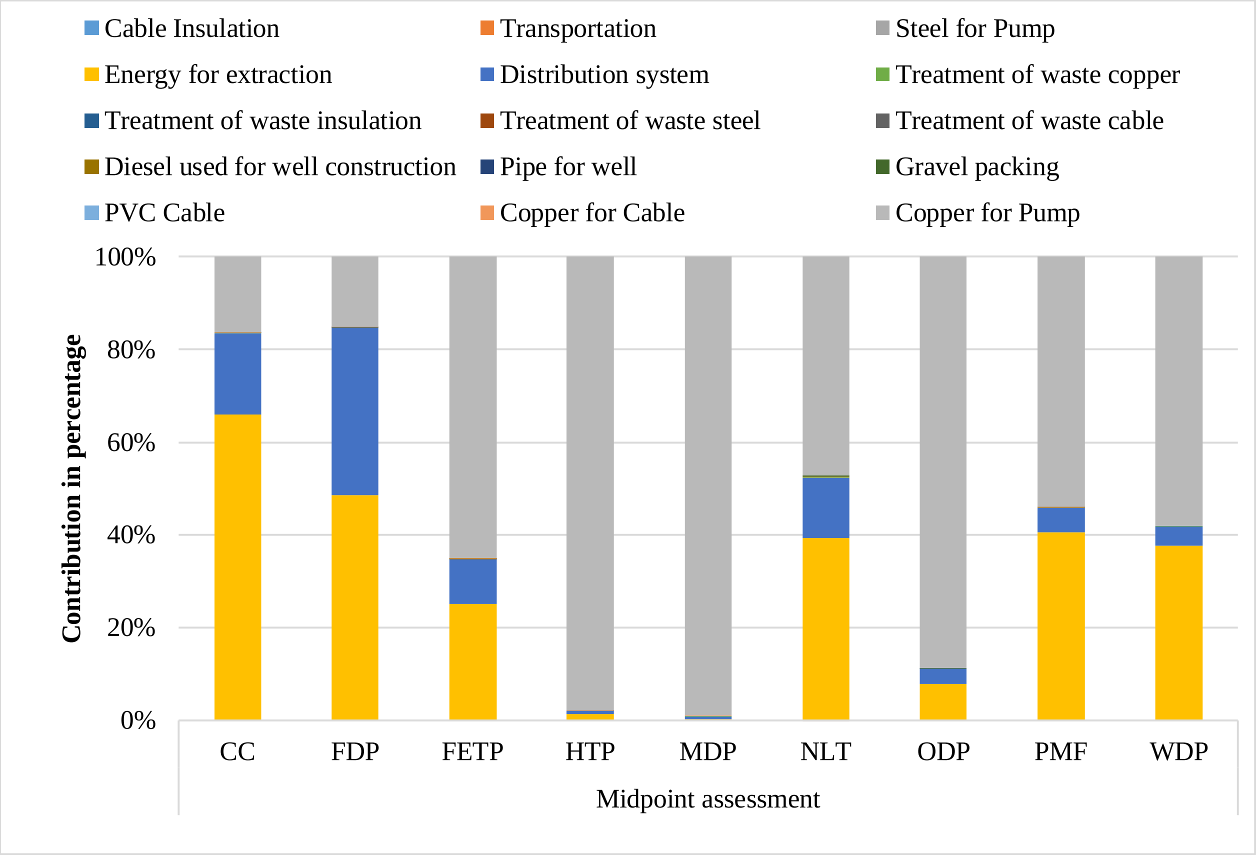


Figure 6.5. Category-wise analysis of midpoint assessment

To visualize the impacts of other model elements, two categories FETP and NLT are discussed in detail for brevity. After removing the most impacting factors in FETP category (copper, distribution system, and energy) from the results of midpoint assessment, it is observed that the consumption of fossil fuel used in the process is the most impacting factor followed by gravel packing, steel, PVC, and asbestos, as shown in Figure 6.6 (a).

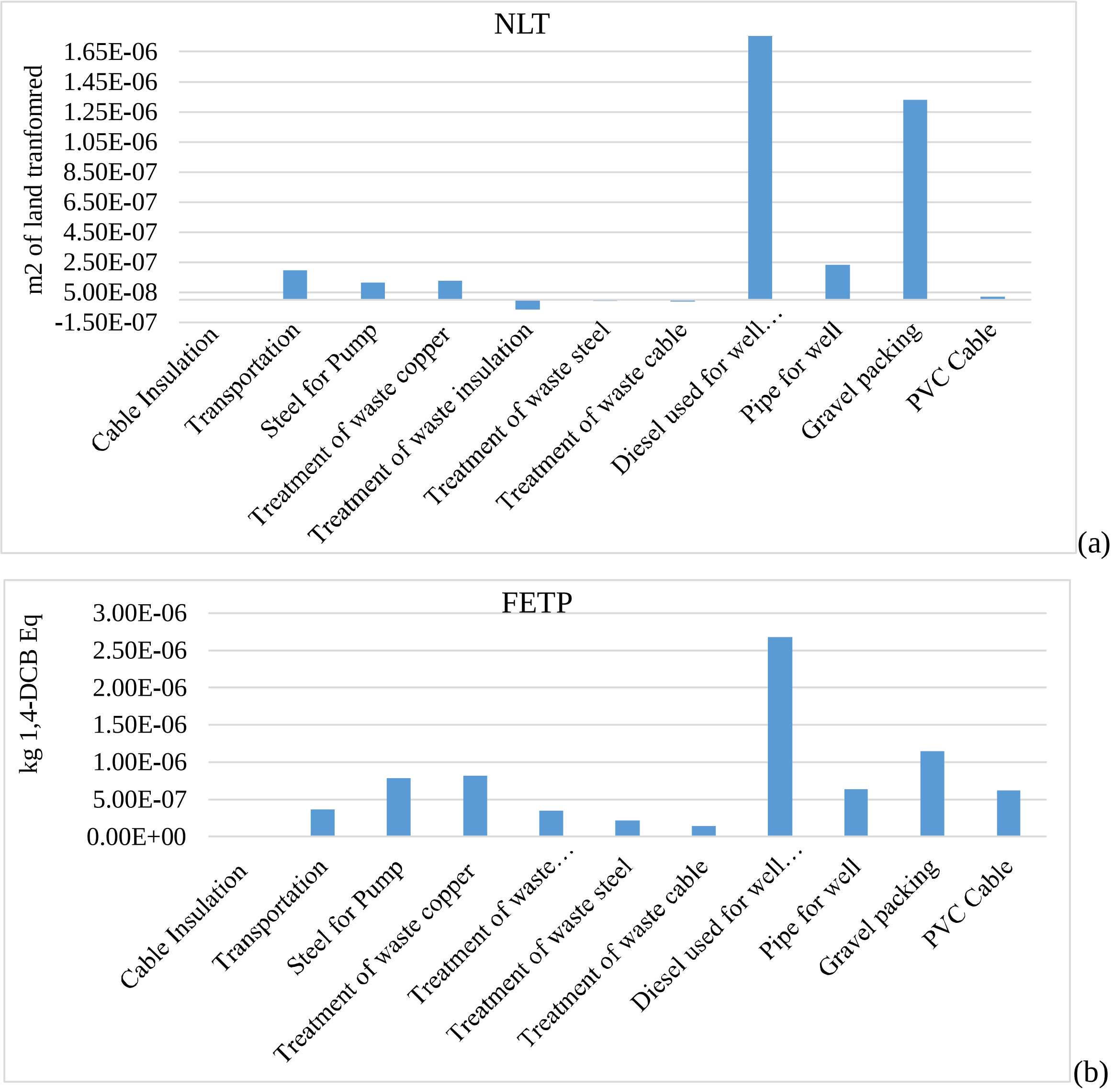


Figure 6.6 (a-b). Analysis of NLT and FETP in midpoint assessment

In the category NLT, consumption of diesel and gravel packing have highest impacts, followed by asbestos, transportation, treatment of waste copper, and steel as shown in Figure 6.6 (b). It is also observed that treatment of insulation used in copper winding, waste cable, and waste steel are environmentally positive in the category of natural land transformation.

### 6.6.2 Endpoint Assessment

In endpoint assessment, the three main categories are ecosystem quality, human health, and resources.

#### 6.6.2.1 Phase Wise Analysis

The phase wise analysis results with respect to all three categories are shown in Figure 6.7. In phase wise analysis of endpoint assessment, WC phase has highest impact on human health and resources categories, whereas ground water extraction phase has highest impact on ecosystem quality.

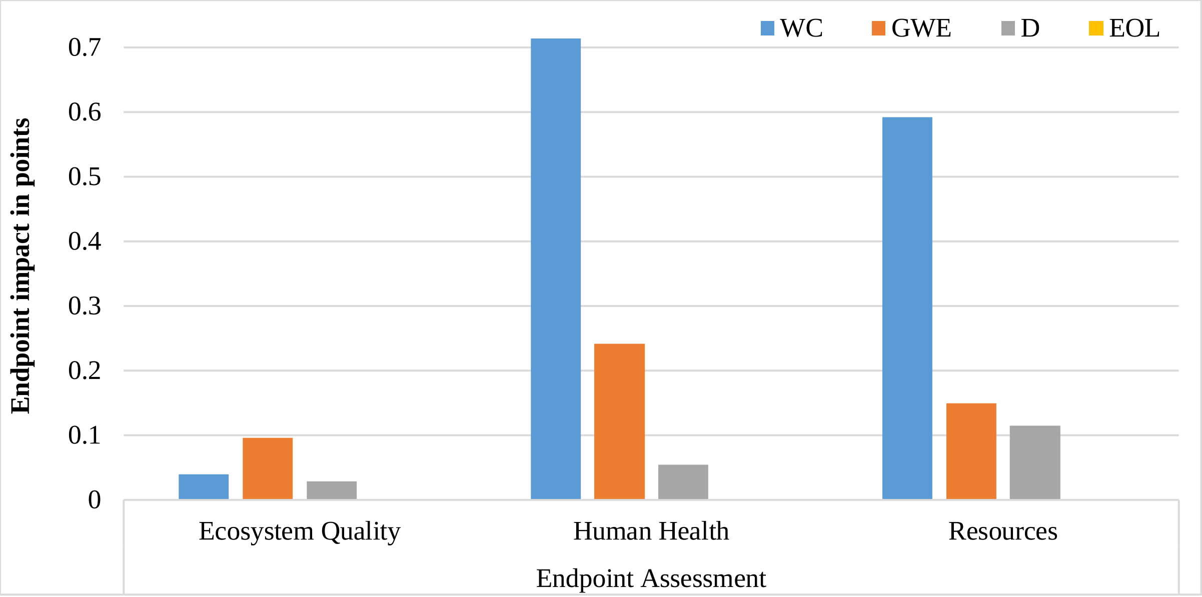


Figure 6.7. Phase wise analysis of endpoint assessment

The EoL phase has negligible impact in all the categories. Moreover, the results followed the same trend of midpoint assessment in the phase wise analysis.

### 6.6.2.2 Category Wise Analysis

In category wise analysis of the endpoint assessment, consumption of copper has been found as the dominating element for environmental impacts in the entire process. This has similar trend as obtained through midpoint assessment, i.e. the consumption of copper has highest impact followed by energy consumed in the process, and distribution system. In the distribution system, HDPE pipe used for irrigation purpose has been reported as one of the substantial environmental hazards. The category wise analysis of endpoint assessment is shown in Figure 6.8.

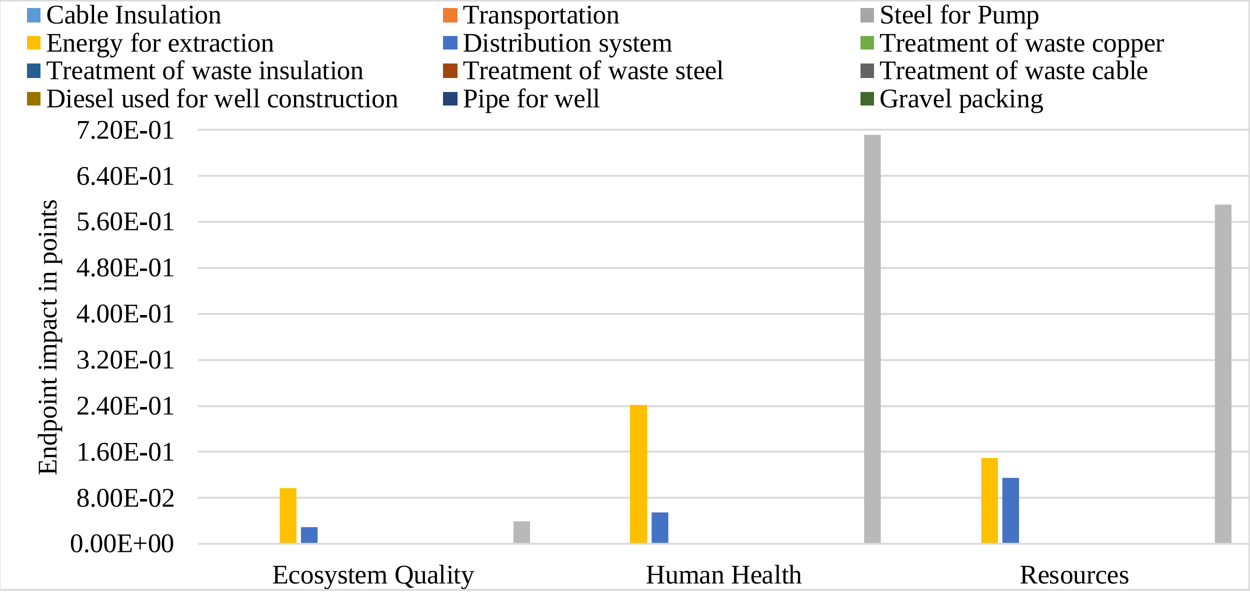


Figure 6.8. Category wise analysis of endpoint assessment

After removing the three major contributors copper, distribution system, and energy consumed in extraction, the graphs are again plotted with respect to the three categories as shown in Figure 6.9. From the results, it has been observed that similar to midpoint assessment, endpoint assessment also prescribes transportation, PVC cable, packing for well, steel for pump as the main contributors to the environment threats.

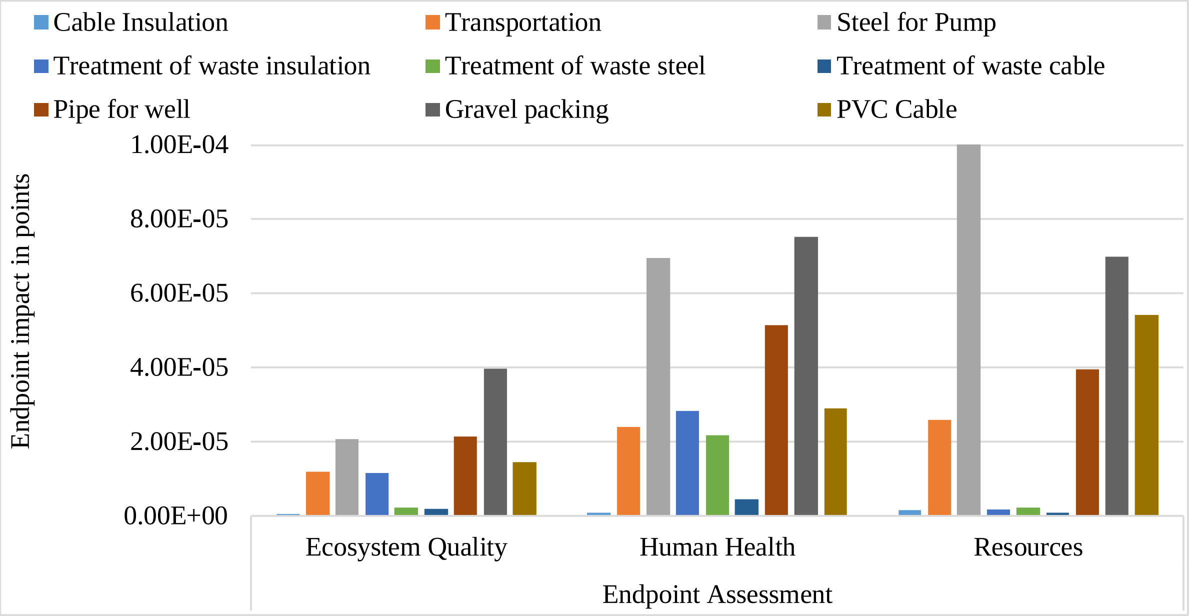


Figure 6.9. Categorical analysis after removing the major contributors (copper, energy etc.)

To assess the impact of water withdrawal, there are various categories and assessment methods. One of the indicators is – Available WAter REmaining (AWaRE) indicator developed by the WULCA (Water Use in LCA), which is a working group of the UNEP-SETAC Life Cycle Initiative (Godskesen et al., 2018). Volume of freshwater can also be considered as water footprint measure, as considered in the present study. The water footprint of the current study has been assessed by WDP category of ReCiPe method. It is found that total water depletion potential value of extracting one litre of groundwater is 1.05 $m^3$.

## 6.7 SUMMARY

In the present study, environmental impacts are assessed for one kilolitre of groundwater used for agricultural purposes in hyper arid region. The study use LCA methodology for the assessment. Software tool Umberto NXT universal and Ecoinvent dataset v3.0 are used for energy and material flow modelling, and well known ReCiPe method is utilized for impact assessment. This study used the global or European data wherever the Indian data was not available in Ecoinvent v3.0.

The findings of the study show that well construction phase has highest impact towards environment hazards. Consumption of copper in equipment throughout the process is the most impacting factor to affect overall categories considered for this research work. This is due to the heavy toxic metals used in its processing. It is observed that heavy metals are easy to identify, process, and work with, which makes them the first choice for any manufacturer. Even though silver is also a good conductor over copper, but its usages are limited due to high cost associated. Secondly, energy consumption plays a key role affecting all the categories of midpoint and endpoint assessment. Results of the present study are comparable to the study by Mo et al., (2011), where embodied energy consumption for a unit water withdrawal from surface water aquifer and ground water aquifer is compared. It is found that the energy consumption is more in the case of groundwater, which is due to the high pumping requirements. The results of the present study can help researchers as well as practitioner (farmers) to develop an understanding of water energy nexus in water scarce regions.

The outcomes of the study demand a suitable groundwater withdrawal policy as the total habitation and agricultural water needs are fulfilled by groundwater only. Along with groundwater extraction, water quality issues are yet to be explored and addressed due to large amount of pesticides and herbicides used for agricultural production in the area. Dependency on groundwater resource in the area clearly demands addressing the issues related to quantity and quality of the subsurface water, so that groundwater can be preserved and sustained for future generations. Another possible solution in semi urban regions is to use treated wastewater for irrigation purposes, which also contains required nutrients for the growth of crops. The after effects of using a treated wastewater in context of social and environmental aspects can be studied further.

Technically tube wells for groundwater extraction should be allocated after analysing the pump test records/reports of the aquifers, so that the groundwater withdrawal rates from the aquifer can be checked. Along with this, the present practice of sprinkler irrigation system should be replaced by drip irrigation system in order to save a huge amount of water in irrigation systems. Solar powered pumps can be a good alternate for distributing the stored water for irrigation. The study limits to environmental impacts assessment and do not consider socio-economic aspects of the groundwater withdrawal/usage.

The next chapter of the study will discuss the chapter wise conclusions of the research work carried out in this thesis along with its limitations and future research direction.

# CHAPTER 7

# CONCLUSIONS

---

## 7.1 OBSERVATIONS FROM THE PRESENT STUDY

The major observations from the thesis are being presented chapter-wise as given below:

### Chapter-1

- 785 million people (1 in 9) in the world are having limited access to freshwater currently.
- The lack of access to safe water is imposing immense pressure on rural areas (where only business is agriculture) in terms of collection and storage of freshwater for meeting the daily domestic requirements as well as for irrigation needs.
- Access to fresh drinking water and droughts in the most productive farmlands are among the biggest threats, planet is going to face in the next decades.
- Stringent and sustainable water management policies are needed in the context of semi-arid, arid and hyper-arid regions of the developing countries like India, where population is ever increasing and demand for fresh water is rising rapidly.
- India uses the largest share of groundwater, which is approximately 24% of the global total with an annual utilizable groundwater availability in India is about 433 billion cubic metres (BCM).

## Chapter 2

- In northwestern hyper arid region of Rajasthan, over exploitation of groundwater has caused deterioration in its quality as well as depletion in the water table.
- The stage of groundwater development is alarmingly high (>146%) for both irrigation and domestic uses.
- No studies were found in the contemporary literature addressing quality as well as quantity of groundwater resources in the study area.
- Remote Sensing, GIS, and multi criteria decision making tools and techniques could be suitable for converting subjective responses in quantitative form for groundwater resource management.
- No studies have been found assessing the groundwater sustainability in single score and environmental vulnerability due to use of groundwater for irrigation purpose in the study area.

## Chapter 3

- In this study, the PCA was carried out using a dataset consisting 14 groundwater samples from Bikaner block.
- The principal component analysis (PCA) helped in extracting principal components to explain the variability in combined population for both pre and post monsoon.
- The output of PCA reveals that the first three eigenvalues together account for over 87.149% of the total variability of the combined population for pre-monsoon and 85.497% for post-monsoon.

- Hierarchical cluster analysis (HCA) supported to identify spatial similarity in the groundwater quality samples from the study area. It also helped in selecting index wells for monitoring groundwater quality in the region.
- The groundwater quality in the study area is affected due to alkali and salinity hazards, which makes it unsuitable for both drinking and irrigation purposes.
- Approximately 41.6% of the samples are under very high salinity hazard, 45.83% of the samples are with high salinity hazard, and rest of the samples falls under moderate salinity hazard.
- About 33.4% of the samples are observed with high alkali hazard, 37.5% of the samples with medium alkali hazard and remaining samples were found to be with low alkali hazard.
- Further, the investigation of groundwater suitability for drinking and irrigation purpose using fuzzy multi criteria decision making, inferred that groundwater management for small scale (farm level) is simpler compare to large scale (regional level).
- The sustainability score of the wells were computed by taking into consideration of ground water quality parameters. These scores indicate that only 40 percent of the wells may be considered for utilization for domestic usages effectively as their sustainability score lies 50% and above.

## Chapter 4

- The soil quality of the region is found to be fertile in nature but over exploitation of groundwater with increased number of minerals has affected the soil quality.