Watershed-level Governance and Management Framework in a Pilot Catchment in India

Beyond the Boundary Technical Modelling and Indicator Report

27th May 2023

Prepared for Frank Water

The expert in **WATER ENVIRONMENTS**

Watershed-level governance and management framework in a pilot catchment in India

Beyond the Boundary Technical Modelling and Indicator Report

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Acronyms and Abbreviations

ACWADAM	Advanced Center for Water Resources Development and Management
App	web application
AR6	Sixth Assessment Report
ATREE	Ashoka Trust for Research in Ecology and the Environment
AWS	Alliance for Water Stewardship
BtB	Beyond the Boundary
BWSSB	Bangalore Water Supply and Sewerage Board
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CII	Confederation of Indian Industry
CSEI	Centre for Social & Environmental Innovation
DEM	Digital Elevation Model
EC	Electrical Conductivity
EO	Earth Observation
ESA	European Space Agency
FES	Foundation for Ecological Security
FW	Frank Water
GIS	Geographical Information System
GRI	Groundwater Recharge Index
GWQI	Groundwater Quality Index
IMD	India Meteorological Department
IPCC	Intergovernmental Panel on Climate Change
ISRO	Indian Space Research Organisation
IWRM	Integrated Water Resources Management

KSIDC	Karnataka State Industrial Development Corporation
LPDC	Litres per Capita Day
MLD	Millions Litre Per Day
NASA	National Aeronautics and Space Administration
NRSC	National Remote Sensing Centre
NGO	Non-governmental Organizations
TMC	Thousand Million Cubic Feet
UN	United Nations
WASH	Water, Sanitation, and Hygiene
WAWQI	Weighted Arithmetic Water Quality Index
WRM	Water Resources Management

Executive Summary

This report presents the final output of project *Watershed-level governance and management framework in a pilot catchment in India,* starting in Oct 2022 until the end of March 2023 and falling under Frank Water's 'Beyond the Boundary' (BtB) umbrella project. The objective was to develop and pilot a framework for mapping, assessing and planning of water resources, using digital mapping and modelling approaches.

The point of departure was a proposed framework of questions by Frank Water (FW) for water resources assessment and the selected study area was Anekal taluk of Bangalore Urban District of Karnataka State in India, where urban development and industrial growth contribute to growing pressure placed on the available water resources.

DHI established the project portal https://beyondtheboundary.waterdss.com/ and a web application providing access to Earth Observation (EO) data. The focus has been on collecting data along the framework proposed by FW, as well as data required for water resources modelling, a key component of the approach.

Data and information were collected from the public domain consisting of observations as well as satellite-based data products that could be accessed without any cost. Data gaps for the construction of the model were found, with hydrometeorological data (both surface and groundwater), water demand and use resulting in the need to make for considerable assumptions and resort to the use of public and free Earth Observation source both Indian and international. Additionally, the project portal and web application were used for presenting model outputs throughout the duration of the project and at consultation workshops.

The model was built for baseline and future periods fitted to the timelines of FW's questions. The results of the different scenario simulations were then used to estimate appropriate indicators to answer the questions. The indicators and how they have been used further demonstrate, how a decision support system could be designed to meet the needs of a taluk with issues such as Anekal.

Next, the conclusions and recommendations are summarized as well as key focus of the assignment finalizing with considerations on study limitations and uncertainty.

Conclusions and Recommendations

It can be concluded that during dry years, the taluk's groundwater is under stress and storage declines. But in high rainfall years, its watersheds receive relatively sufficient recharge, having a stabilizing and replenishing effect on storage. As for the near future, groundwater availability is likely to reduce.

Regarding groundwater quality, it was concluded that the data available to the project did not have enough time coverage to carry out a sound assessment.

It has been shown that when official monitoring data from authorities is sparse, it is possible to use Earth Observation based data to fill some of the gaps successfully.

It can be concluded that models can be used to support the work of NGOs such as MYRADA. Especially, when there is little data, hydrological and water resources models can help improve the understanding of the physical system.

In addition, the indicators estimated during this assignment could be used operationally by FW's partners to support the communities they work with, and the approach piloted in Anekal could be replicated to other areas in Karnataka and India.

It is recommended that in a follow up phase of the BtB project, socio-economic, institutional and policy dimensions and specific activities are contemplated. At the high level, acceptance and even vetting of the outputs by local government can be promoted, whereby at the technical level, indicators pertaining to these categories can be added, to name a few straightforward examples.

It is also recommended that a review of the intended users of BtB technological/scientific outputs is carried out. These could include government and private sector. The modelling exercise and all upstream/downstream steps involved, for building a planning and decision-making framework, would need to be more extensive and detailed, would require end user involvement and include the conceptualization of scenarios and outputs carrying probability and likelihood.

Not only this, but it would also require a large investment in understanding what framework is currently used and how, in order to fit the approach to the end users.

Direct linkages with the regulatory framework and the model outputs can be derived and could result in a strengthened backing of conclusions for planning and management of water resources. A co-design process should then be followed to design a web app with easy-to-read dashboards, displaying exactly what the project partners and stakeholders want and need.

Indicator Framework

To address the proposed framework of questions by FW and based on DHI's leading and decades-long water resources management experience, the questions were answered using indicators grouped into four categories 'LULC' (land use land cover), 'water quality', 'climate' and 'water resources'. The correspondence between the indicators and the questions is presented in Table 4.1.

A useful indicator should be relevant for monitoring the state of the resource or issue in question, be easy to interpret, be able to give information on the current status and the status in relation to the historical change and be based on available data or information. Also, the more defined an indicator is, the less room there will be for later confusion or complications.

The indicator framework proposed can help FW and partners understand the current state of water resources, the changes in these resources and whether or not interventions produce the desired effect. It is also possible for FW and partners to use it to identify risks. In addition, the indicators and the tools piloted can be used as a learning tool for basin or catchment organisations/other users.

We consider the approach and indicators provide a starting point that can be adjusted and complemented to match FW specific user needs, provides an online tool for stakeholders to share their indicator assessment with others to allow for consistency (it helps if when actors are all measuring the same thing) and, used as a tool for storing indicator information to support future design of decision support systems (DSS).

The indicators proposed are listed below to sum up:

- Land use land cover change: annual variation in the area of specified land use land cover classes at the watershed level
- Monthly precipitation and temperature: monthly accumulated and average monthly time series for a specific area
- Long term mean monthly precipitation and temperature: monthly mean considering the period of record for a specific area
- Climate change factors: ratio (in the case of delta change factors) or the difference (in the case of absolute change factors) between the average in the historical model run (1995-2014) and the projection model run for the five socioeconomic pathways (SSPs) SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 evaluated in the IPCC AR6
- Current water demand disaggregated by sector: amount of water required in the baseline scenario by domestic, agricultural, industrial and construction sectors in Anekal
- Current water use disaggregated by sector: simulated amount of water used by each category: domestic, agricultural, industrial and construction in Anekal
- Current total amount of water available for use: simulated groundwater recharge minus the natural discharges a.k.a. extractable GW resource for the baseline scenario

- Projected water demand disaggregated by sector: amount of water required in the future scenarios by domestic, agricultural, industrial sectors in Anekal
- Projected water use disaggregated by sector: simulated amount of water used by each category: domestic, agricultural, industrial in Anekal
- Projected total amount of water available for use: simulated groundwater recharge minus the natural discharges a.k.a. extractable GW resource for the future scenarios S1 to S4
- Groundwater Recharge Index: index describing the groundwater recharge as a percentage of the recharge in the baseline scenario
- Critical/stressed groundwater: official formulation used by the District Groundwater Office, Groundwater Directorate, and the Central Ground Water Board, South Western Region, Bangalore
- Lake storage volume: simulated mean annual stored volume in a lake

Water Resources Modelling

Groundwater being the major source of supply to most of the users in Anekal taluk, sustainable development and management of this resource is key to ensure access for local communities, productive industries, and a healthy environment. Therefore, focus was placed on assessing the status of groundwater resources at the watershed level. Modelling approach is adopted to understand the baseline conditions in the Anekal taluk by establishing a water resource model to account for the major water use categories – Domestic, Industrial and Agriculture – and for future urban development plans and projected climatic conditions.

DHI's own water modelling software – MIKE HYDRO Basin (MHB) – was used in this assignment, a simulation tool for water resources modelling and water allocation investigations. Baseline conditions i.e., climatic, hydrological, land use along with different water usages – are defined in the model for simulation period 2010 to 2021 (known as S0). Four future scenarios (S1 to S4) were built to understand the implications on the state of water resources in Anekal taluk considering the projected water uses (based on the proposed urban developments until year 2031) and projected climate (until year 2040). These are summarized as:

- S0: conditions in the watersheds in the baseline period from 2010 to 202; no planned developments, no climate change projections
- S1: developments inferred from LULC and available masterplans, expected to be in place by 2031, no climate change projections
- S2: S1 and SSP1-1.9 climate change projections, near future (2021-2040) 'low emissions'
- S3: S1 and SSP2-4.5 climate change projections, near future (2021-2040) 'middle of the road'
- S4: S1 and SSP3-7.0 climate change projections, near future (2021-2040), 'high emissions'

To understand the state of Anekal water resources, FW proposed a framework that encompasses and informs on the key questions relevant for the assignment. Through the modelling exercise and processing of earth observation and ground/based data, results are interpreted and explained through defined 'indicators' specific to the questions.

Modelling and Analysis of Watershed Key Issues

Through the modelling exercise, it was observed that during dry years, when there is less rainfall, less recharge is generated which puts the taluk's groundwater under stress. The groundwater storage declines. But in high rainfall years, typically more than rainfall of 800 mm of annual rainfall, the watersheds receive relatively sufficient recharge, having a stabilizing and replenishing effect on storage.

Below are the key findings through the modelling exercise:

- The total amount of water received annually in Anekal taluk as simulated by the model (for 11 hydrological years from 2010 to 2021) is 43 million cubic meter (mcm) per year on an average.
- Land use witnessed changes with increased area from 2010 to 2022 in 'Urban / built up' class from 8.82% to 16.62%, 'Bare/sparse vegetation' from 1.59% to 1.62%, 'Open forest – mixed' from 8.56% to 6.59% and 'Permanent water bodies' from 2.45% to 2.65%. This change was at the expense of decreases in 'Cultivated and managed vegetation/ agriculture (cropland)' 67.24% to 64.57%, 'Herbaceous vegetation' 6.87% to 2.23% and 'Shrubs' 4.47% to 3.43%
- The total current water demand in Anekal taluk is 46 mcm per year on average and it is expected to increase to 48 mcm per year on average in future time period (2021-2040). The agriculture water demand shares the maximum percentage of the total water demand (>90%)
- About 93% of the current water demand is being met in Aneka taluk, where in future it is likely to be 90% for low and moderate emission scenario and 99% in high emission scenario.
- The current aquifer recharge or groundwater recharge is 43 mcm per year on an average. Groundwater recharge index reflects on the percentage change of the groundwater recharge with respect to the baseline The relative change is maximum for high emission scenario where recharge is expected to increase by 17% due to high variability in monsoon months. For other low and moderate emission scenarios, the relative change is minimal and falls in the range of 0 to 3%. The area in the east and south of Anekal taluk are more likely to be under stress due to overall high agriculture demand. The severity is expected to be high in dry years.

All the results are available on the BtB portal developed.

Limitations and Uncertainties

It is important to note that the models used for this study, while checked and calibrated to the best extent possible, have some limitations and uncertainties (see sections 3.2.5 and 3.3.3). Most importantly, there has been a lack of data for e.g. observed river discharge and groundwater levels, population, agricultural and industrial demands, etc. Several assumptions had to be made to support the description of those aspects for which data was missing. In addition, climate change projections are by nature uncertain.

For these reasons, the conclusions presented should be taken as an indication of the impact and trends of future development and climate change rather than taken as representing absolute magnitude of impacts. More accurate data on surface water, groundwater, water demand and use can lead to this, reduction of error would be expected, but moreover, other methods may become available. Future work on climate change projections should focus on clustering a large number of climate change scenarios with statistical analysis of likelihood and confidence in the different scenarios.

1 Background

This report constitutes the final deliverable of project *Watershed-level governance and management framework in a pilot catchment in India* implemented by Frank Water (FW), delivered by DHI from October 2022 to March 2023, with the objective to develop and pilot a framework for mapping, assessing and planning of water resources, using digital mapping and modelling approaches. This project falls under FW's 'Beyond the Boundary' (BtB) umbrella project. In turn, the BtB project aims to support collaboration between local communities and corporate production sites to contribute to good water governance and achieve safe and sustainable water, sanitation, and hygiene (WASH) services and water stewardship.

Key partners of Frank Water are non-governmental organisations (NGOs) MYRADA and the Foundation for Ecological Security (FES). The Advanced Center for Water Resources Development and Management (ACWADAM) has been involved as a workshop partner. Additional stakeholders also took part in the project are hub partner Bala Vikasa and knowledge partner Centre for Social and Environmental Innovation (Ashoka Trust for Research in Ecology and the Environment (ATREE)).

The selected study area was Anekal taluk of Bangalore Urban District of Karnataka State in India, based on its level of industrial growth and growing pressure placed on the available water resources for local communities and the different economic sectors. The knowledge and technological outputs of this project are intended to demonstrate how science-based approaches may lead to increased understanding and awareness of current and future states of water resources to promote sustainable use by the different sectors.

Task 1 'Inception and overview' started in October 2022 and culminated with the first project workshop and approval of the Inception Report (December 2022). Task 2 'Data collection and additional survey' started in parallel with Task 1, as the project team and FW collected data and information following the data requirements list produced by DHI. This list was presented at the stakeholder inception workshop and gaps discussed. DHI established the project portal and a web application providing access to Earth Observation (EO) data. A water use survey and institutional assessment at the taluk level was carried out by MYRADA and FES.

Main activities of Tasks 3 and 4 were the following:

- participating in a technical workshop on the 13th February 2023 organized by FW providing an opportunity for the project partners and stakeholders to meet in-person in Bengaluru developing the water resources model and establishing modelling scenarios
- a field visit on the 14th of February 2023 to Anekal taluk
- estimate an indicator framework based on the BtB proposed framework for mapping, assessing and planning of water resources, using the modelling results.

This report presents a detailed description of the findings of the technical workshop, the modelling work, discussion of results, indicator framework, scenario analysis, conclusions and recommendations for future work. The description of the technical workshop and field visit are included in appendices A and B. Technical details are included in Appendix C for consultation.

2 Stakeholder Consultation

On the 13th of February 2023, a technical workshop was organized by FW gathering the BtB project partners and stakeholders. The purpose of the workshop was to share knowledge and provide feedback to the technical approach, whereby the stakeholders described their internal processes related to water demand and use and assessed the proposed modelling and indicator framework. The list of attendees, agenda and key findings are enclosed in Appendix A.

DHI was responsible for three sessions of the technical workshop. These were organized logically to afford the participants an introduction to the portal and EO-based data web app (1), before they use it to investigate possible scenarios (2) and discuss indicators for their evaluation and comparison (3). The sessions summarized below, involved pre-prepared guides to guide the participants' interaction with the portal and their group discussions.

Session 1 – BtB portal and earth observation data app

The portal https://beyondtheboundary.waterdss.com/ has been the vehicle for sharing data and information with FW and project partners, especially during workshops but because there is no need to log in and access is public to all users, throughout the project lifetime.

The purpose of this session was to provide an overview and understanding of available near real time data for water resources assessments, where participants interacted with some of the most common types of variables available for viewing, analysing and downloading. Ultimately, the intention was for participants to learn how to navigate the app and to learn how satellite-based data could be used for water resources management providing near real time and spatially distributed information.

Various satellite-based rainfall datasets and a rainfall derived drought index were inspected as an example, amongst others.

Session 2 – Presentation of the modelling approach

At the time of the technical workshop, results of the preliminary baseline model had been uploaded for inspection by the stakeholders. The model was set up for Anekal taluk of Bangalore Urban district at watershed scale, with a total 7 watersheds (see snapshot in Figure 2.1).

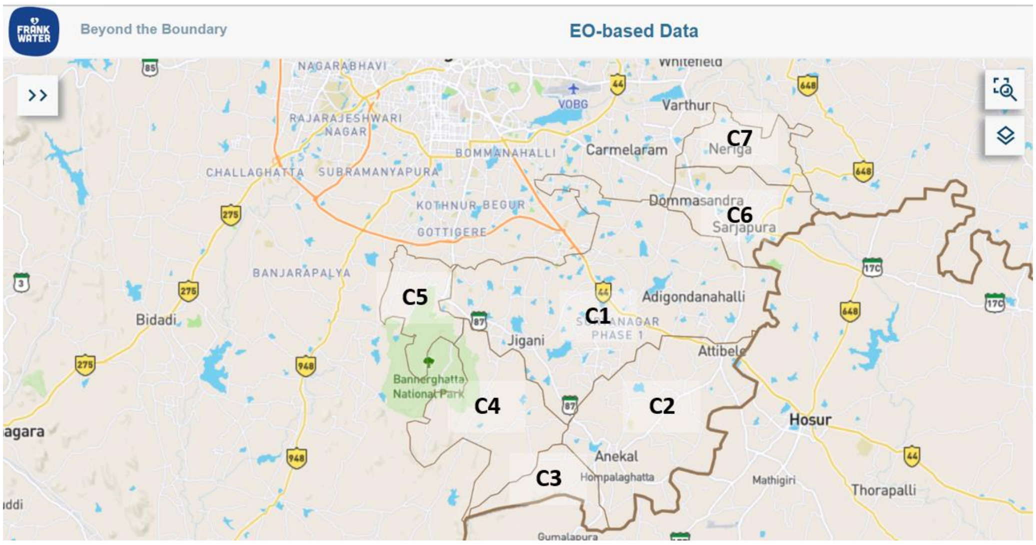

Figure 2.1 Snapshot of the portal showing a background map and the watersheds of baseline model as light brown polygons

Participants were asked to observe the result time series of watershed average rainfall, simulated watershed runoff, water demand, groundwater abstraction and depths, for catchments C1 to C7.

They were asked to discuss the differences between watersheds including which were approaching a near- critical state.

Session 3 – Presentation of indicator framework and future scenarios

The third and last session, invited workshop participants to explore the future projected changes in key climate variables under each of the IPCC's latest Socioeconomic Pathways (SSPs) scenarios, based on a review of climate change factors. The objective was to better understand the differences between the latest projections of climate change in the area, and to select which are most relevant to use going forward.

The guide developed for this session, focused on precipitation, evapotranspiration and temperature. Though the latter is not used by the water resources model it is an important factor when evaluating the impact of climate change, as higher temperatures cause a decrease in soil moisture, increase in evaporation and intensification of the dry season.

Participants discussed how the projections varied for each climate variable and in between, to uncover expected inter-relations. In addition, the differences across scenarios for the 2041-2060 projection period: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5.

They were then asked to select which SSP(s) should be used to model the impact of climate change in this study from a perspective of best, worst, and intermediate cases, depending on the relevance and utility for their work.

Finally, the list of possible indicators was presented and discussed. Participants were asked which ones provide information that is useful when working with local communities, and if there were any missing from their perspective.

3 Model conceptualization and setup

This chapter describes the final conceptualization and setup of the water resources model. It is a result of the incorporation of the feedback received from FW and stakeholders to the preliminary setup presented at the technical workshop in February 2023.

3.1 Modelling software

DHI's software MIKE HYDRO Basin[1] (MHB) was used, a simulation tool for water resources modelling and water allocation investigations.

Technically it is a network model in which the rivers and their main tributaries are represented by a network of branches and nodes as shown in Figure 3.1. The branches represent individual stream sections while the nodes represent confluences, bifurcations, locations where certain water activities may occur, or important locations where model results are required.

Basic input to the model consists of time series data of various types: catchment run-off, meteorological time series, data pertinent to each water supply such as an irrigation scheme, additional data describing hydraulic conditions in river reaches and channels, groundwater characteristics etc.

An important feature is the ability to handle users with multiple priorities from any number of different sources as well as a source with priorities for any number of different users. Often, several users may want to receive water from the same resource. Within the model concept this situation is represented by several user (off-take) nodes connected to a single supply node. Allocation algorithms determine how water is distributed among several users in case of conflicts.

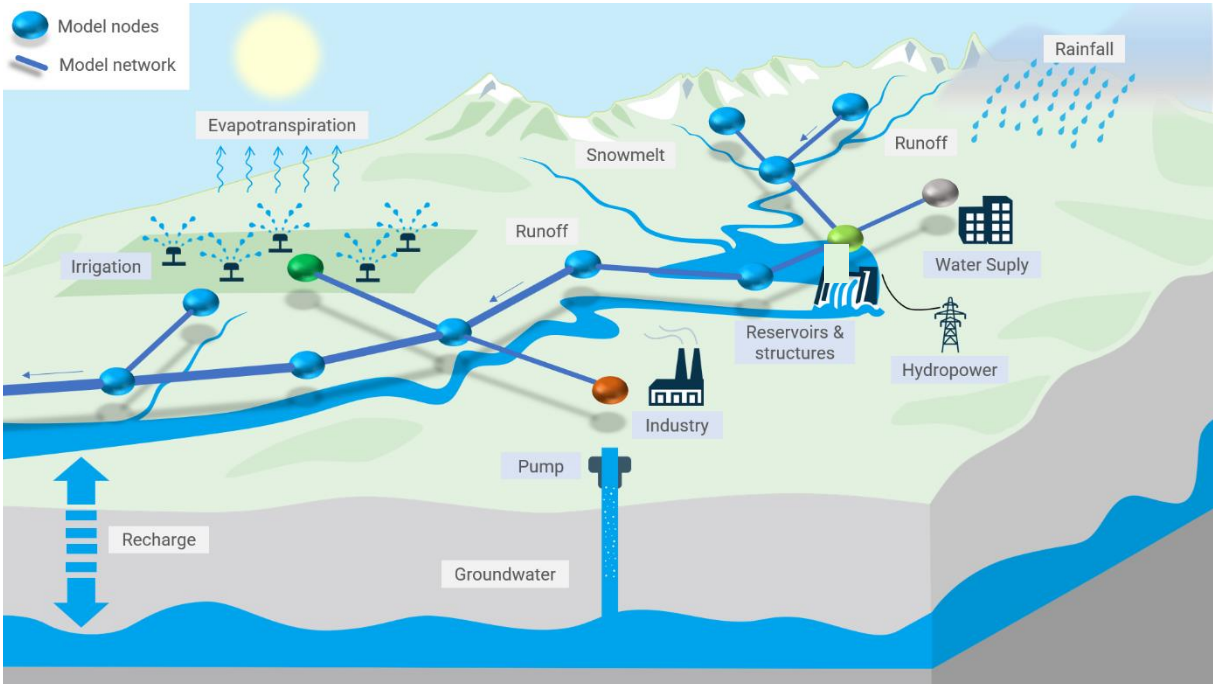

Figure 3.1 Illustration of the MIKE HYDRO Basin model network

The facility to handle priorities from a user perspective as well as from the resource perspective makes the model flexible in its application. The model is also able to look at land use and different types of institutional arrangements such as fractional allocations and capacity sharing (water

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[1] More information on the water resources modelling software applied in this study can be found at https://www.mikepoweredbydhi.com/products/mike-hydro-basin

banking) which make it even more useful in terms of different operating criteria to manage a system.

The rainfall-runoff module inside MHB, known as the NAM model, is a conceptual model representing the land phase of hydrological cycle simulating precipitation over land, interception, evaporation, transpiration, infiltration, and percolation along with horizontal flows (overland, interflow and baseflow). The NAM model includes four storages i.e., snow, surface, sub-surface / root zone and groundwater. In this study, the NAM model is used to simulate catchment runoff including overland flow, interflow and baseflow, uses three storages surface, lower zone storage and groundwater storage and forms the basis of all the calculation presented hereafter in the report.

The groundwater module in MHB assumes that the lateral boundaries of subsurface (groundwater) and surface catchments are the same. The groundwater storage (aquifer) is conceptualised as a linear reservoir model with one or two layers. The conceptual structure of the two-layer groundwater component is shown in Figure 3.2. As illustrated groundwater interacts with the surface water via groundwater recharge, groundwater discharge and seepage from river branches, reservoirs and connections. Moreover, when the water table of the shallow (upper) aquifer reaches the land-surface, it starts to spill directly into the river. Finally, groundwater from the deep aquifer can be pumped by water users (unless a one-layer aquifer has been specified then pumping takes place from the shallow aquifer).

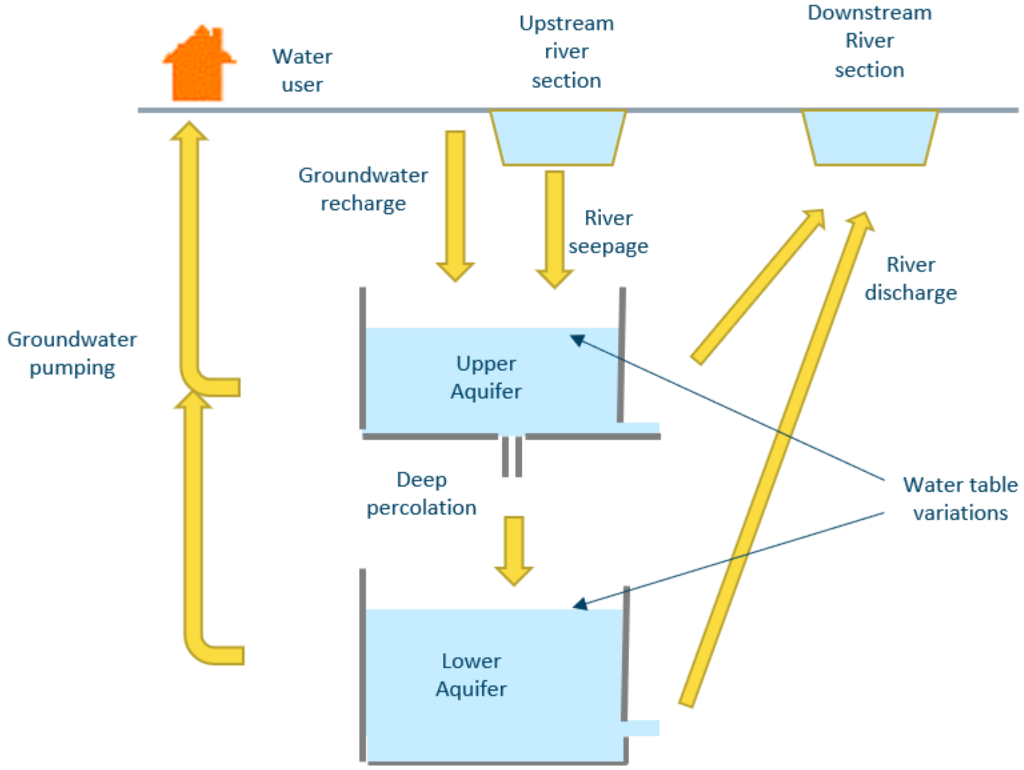


Figure 3.2 Simplified schematization of the groundwater module of the model

3.2 Baseline scenario

The baseline scenario represents the time period 2010-2021 i.e., from 01-Jun-2010 to 31-May-2021, reflecting the climate, hydrologic and assumed/estimated water consumption conditions for Anekal Taluk within that period. Climate, land use as well as hydrological data for the last 10 years have been used to build this scenario.

3.2.1 Climate

The rainfall-runoff model requires precipitation and potential evapotranspiration, the sub-sections that follow discuss these variables in brief.

Precipitation

Data for this climatic variable was sourced from the Indian Meteorological Department (IMD), providing a dataset freely of gridded daily rainfall with a resolution of 0.25^0 (~28 kms). This data was used as input in the model to generate catchment runoff for the baseline period. The IMD datasets were downloaded from IMD website followed by extraction of daily time-series per grid cell. Figure 3.3 and Figure 3.4 below show the annual and mean monthly rainfall of Anekal Taluk for the baseline period. The maximum rainfall is observed in year 2017 with 1290 mm of annual rainfall, followed by 1128 mm in 2015 and 1111 mm in 2011. The minimum rainfall occurred in year 2018 with 435 mm.

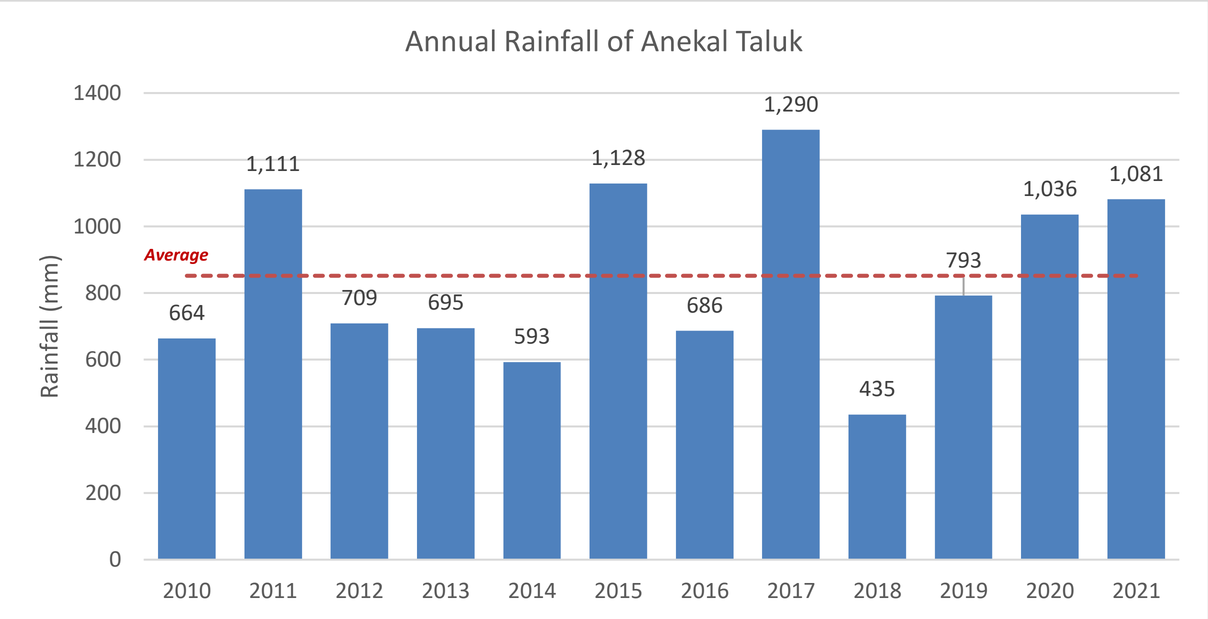


Figure 3.3 Annual variation of total weighted rainfall in Anekal taluk based on IMD observed dataset.

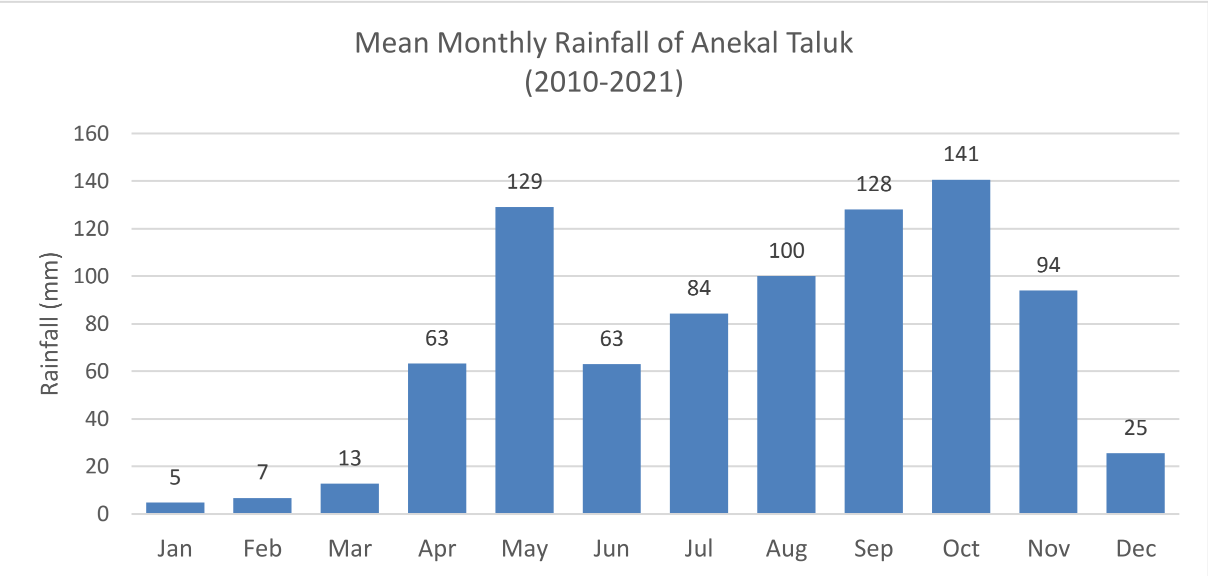


Figure 3.4 Mean monthly rainfall of Anekal taluk for the baseline period.

Potential Evapotranspiration

Potential evapotranspiration rates (PET) were sourced from ERA5 global gridded dataset which is the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate. Reanalysis combines model data with observations from across the world into a globally complete and consistent dataset using the laws of physics (data assimilation). The dataset has a resolution of 0.25^0 (~28 kms). Figure 3.5 and Figure 3.6 show the annual and mean monthly PET of Aneka Taluk for the baseline period based on ERA5 global dataset. The maximum annual PET is observed for the year 2012 (2029 mm) followed by years 2016 (2007 mm), and 2014 (1955 mm). The minimum annual PET is observed for the year 2021 (1746 mm).

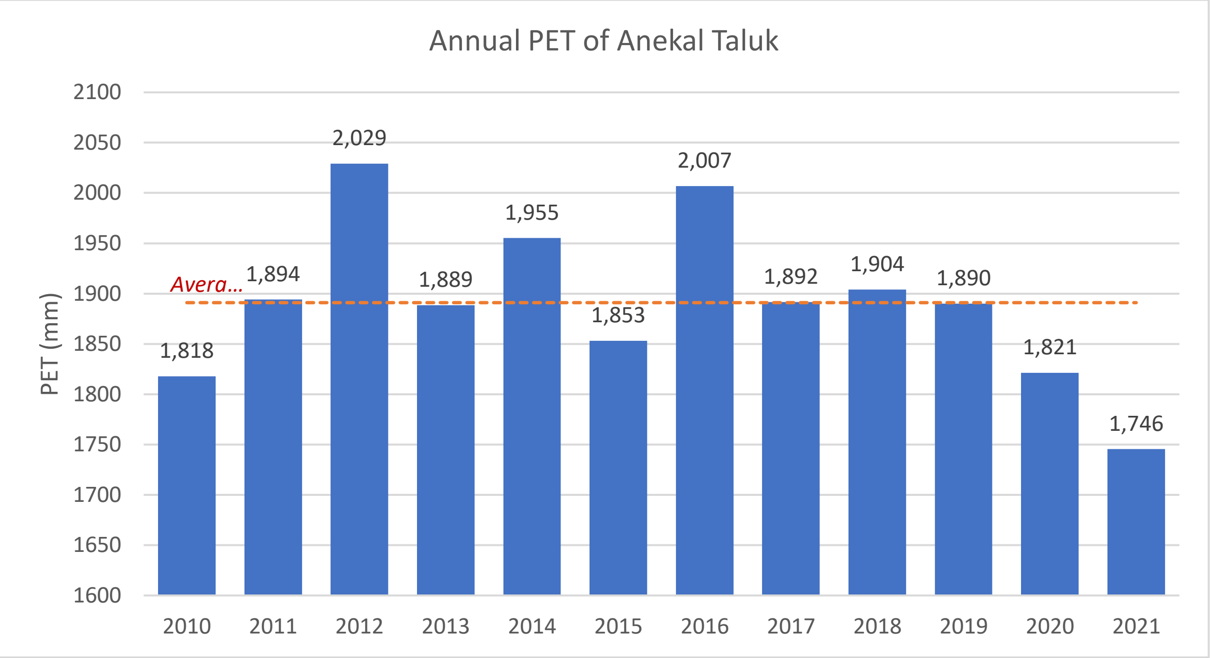


Figure 3.5 Annual variation of potential evapotranspiration in Anekal taluk based on ERA5 reanalysis dataset

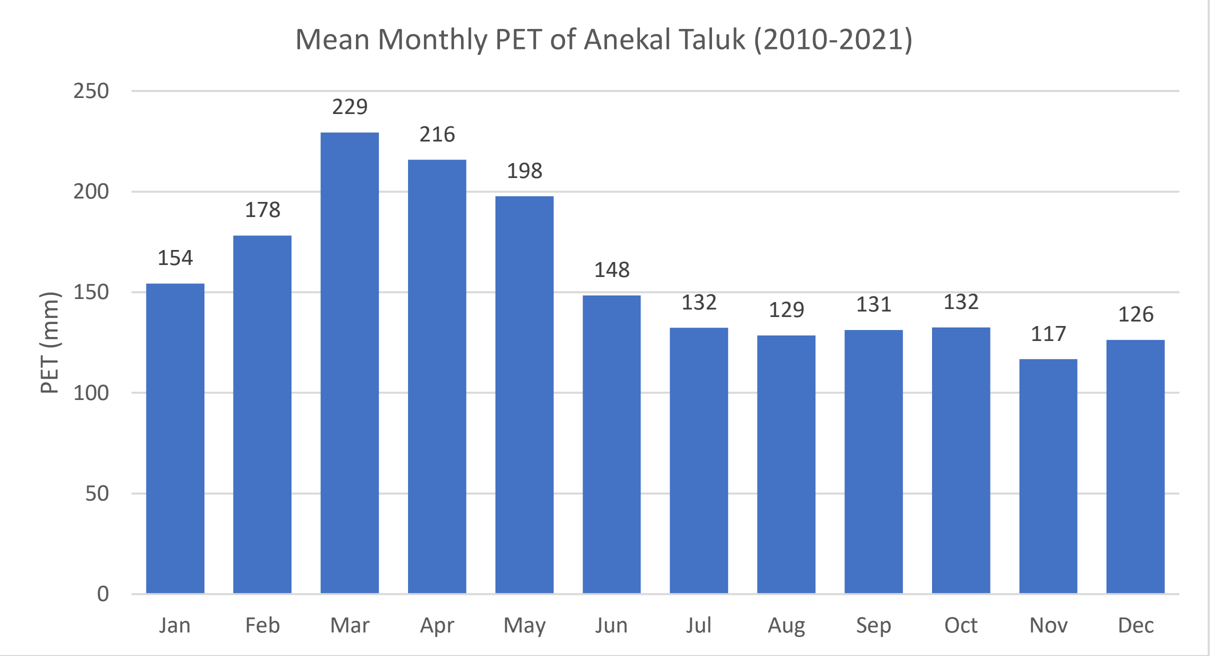
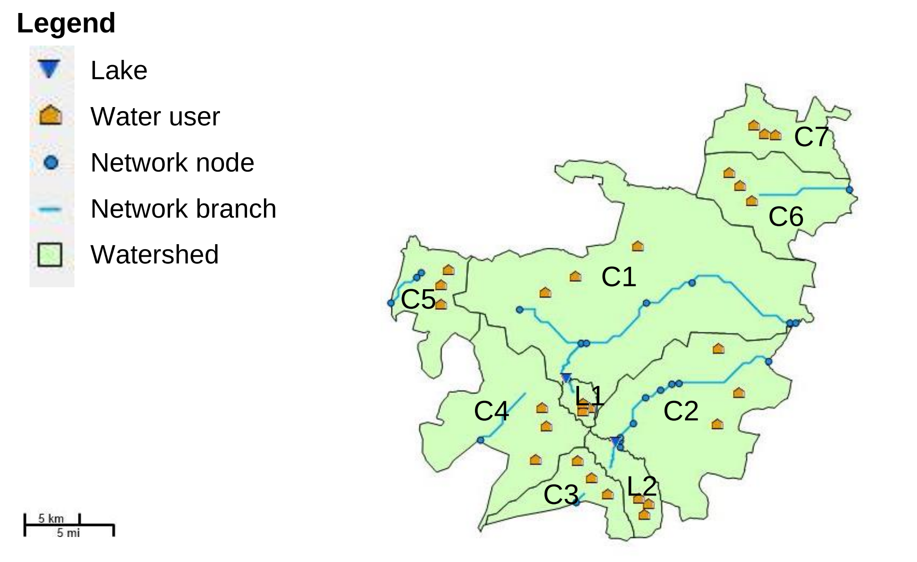


Figure 3.6 Mean monthly PET of Anekal taluk for the baseline period

3.2.2 Model Setup

As explained in 'Data collection and Mapping Report', Anekal taluk is drained by two different basins. For modelling purposes, Anekal taluk is divided into watersheds based on the HydroBasins dataset Lehner et al (2013). In total, there were seven watersheds delineated for Anekal, presented at the technical workshop. This delineation was then updated to include two lakes suggested by FW, hence the two watersheds C1 and C2 were further divided into L1 and L2, resulting in the final number of nine watersheds for the modelling study. It is assumed that there are no lateral inflows in the Anekal taluk along the administrative boundary and rainfall is the primary source of water. Figure 3.7 shows the location of watersheds forming the units for the assessment.



Watershed	Area (km^2)
C1	212
C2	104
C3	26
C4	76
C5	33
C6	51
C7	34
L1	6
L2	18
Total	*560*

Figure 3.7 Baseline model setup showing delineated watersheds and model objects namely, lakes (inverted triangles), water users (orange pentagons), catchments (light green polygons)

3.2.3 Water demand

Water use categories identified for the baseline model falls under three categories – Domestic, Industrial and Agricultural. Estimates that were already available or that are derived from secondary sources are used for defining water demand for those categories in the model.

Domestic Category

This category refers to water required by population for domestic purposes including drinking, cooking, bathing, washing hands, face etc., Household sanitary purposes, private gardening, domestic animals, and private vehicles. This category is calculated based on the population data from 2011 India Census.

Domestic water demand for each watershed is computed based on the aggregation of the domestic water requirement per capita. As per the Indian Standard, IS:1172-1171, the average daily domestic demand for urban and rural population was considered for the calculations – Rural with 55 Litres Per Capita per Day (LPCD) and/or Urban 135 LPCD. Village wise population and its category is used to calculate the domestic demand per watershed. The total domestic demand per catchment is computed as population times daily per capita requirement.

In addition, the surveyed information based on 521 survey points collected by FW partner MYRADA and CGWB assessment reports /6/,/7/,/8/,/9/,/10/ was used to corroborate the daily domestic demand.

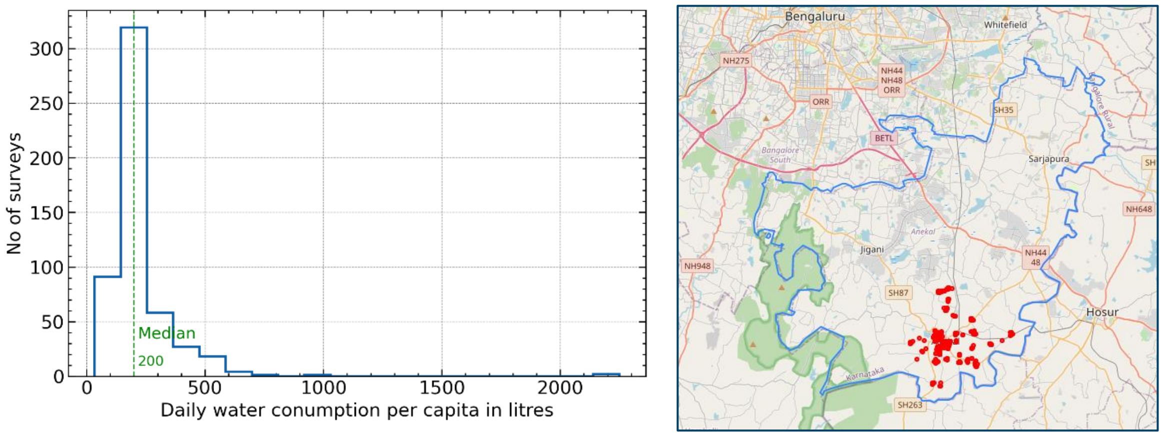


Figure 3.8 **Domestic surveyed data from MYRADA. The left plot shows the histogram. The right image shows the surveyed locations.**

Industrial Category

Estimates of industrial water demand were taken from the CGWB assessment reports /6/, /7/, /8/, /9/, /10/ and other published reports /14/. In the absence of any other alternative data source, the total industrial demand of Anekal taluk is apportioned to watersheds based on available estimates on the industrial areas. From the LULC map of Anekal taluk, following interpretation is used to apportion the total industrial demand into each watershed.

Table 3.1 **Percentage distribution of Anekal taluk's industrial water demand**

Watershed	C1	L1	C2	L2	C3	C4	C5	C6	C7
Industrial demand distribution (%)	37%	3%	20%	10%	10%	5%	5%	5%	5%

Agricultural Category

This category refers to the water required for irrigating crop fields. The demand is calculated based on the available crop information including crop type, cropped area, crop water requirements and irrigation need. The calculation is performed using the Food and Agriculture Organization method /12/ for estimation of irrigation water needs, in the following steps.

1. Crop type information is obtained from Agriculture department /13/, State of Karnataka, for the year 2021. The statement lists out the Kharif, Rabi and Summer crops grown in Karnataka state. For the present study, it is assumed that the same crops are being grown in the region and maintain the same cropping pattern throughout the baseline period.

2. Cropped area information is obtained from the LULC map of 2021. A total area of 179 km^2 is calculated for Anekal taluk.

3. Crop water requirement (in mm) of each crop per growing season is obtained from FAO /12/. The total crop water requirement per crop is then distributed per day on the basis of crop factor and development stage period.

4. Daily crop water requirement depths are then reduced by effective rainfall depths following FAO guidelines to compute daily irrigation needs.

5. The daily irrigation needs is then multiplied by the cropped area (m^2) to compute daily volumes (m^3)

Table 3.2 presents the crop name, type, and other information required for computation of the total agricultural demand of Anekal Taluk. The total calculated demand is then apportioned to nine watersheds based on the cropped areas obtained through GIS analysis using watersheds boundary.

Table 3.2 Crop water requirements

S.N.	Crop	Type	Total growing period	Total Water Requirement (mm)*	Percentage of Cropped area**	Cropped area (sq.km)
1	Rice	Kharif	125	700	16%	29
2	Ragi	Kharif	120	450	10%	18
3	Maize	Kharif	100	400	17%	31
4	Tur	Kharif	120	500	16%	29
5	Groundnut	Kharif	120	500	8%	14
6	Soyabean	Kharif	130	650	3%	6
7	Cotton	Kharif	180	1000	3%	6
8	Sugarcane	Kharif	220	1200	3%	6
9	Jowar	Rabi	120	450	10%	18
10	Bengalgram	Rabi	120	500	12%	22
				Total	100%	179

*FAO based /12/, ** /13/

The total demand of all crops is further compared and adjusted with irrigation use reported in CGWB assessment reports for different years. Below table shows the total calculated demand considered for the model simulations.

Table 3.3 Total demand considered for model simulations

Category	Domestic	Industrial	Agriculture
Demand (mcm)	4.26	0.65	41.00

3.2.4 Calibration and validation

The rainfall runoff model was first set up for a larger catchment area than Anekal taluk, as shown in Figure 3.9. The catchment delineated has its outlet near ‘Gummanur’ village in Dharmapuri district in the state of Tamil Nadu in India. This is done to calibrate the model parameters by comparing observed and simulated discharge at ‘Gummanur’ gauging site. Daily flow observations for the time period 2001-2018 were available and were compared with simulated discharge.

Calibration is a procedure of fine-tuning of model parameters to get the desired range of outputs. In the present study, calibration is performed in two steps:

The first step involved calibrating against daily flow measurements recorded at the ‘Gummanur’ site in Dharmapuri district in the state of Tamil Nadu in India. This step is performed to calibrate the rainfall-runoff model’s parameters to generate acceptable range of simulated discharge. The rainfall-runoff model adopted i.e. the NAM model, simulates discharge as one of its outputs. The simulated discharge comprises overland flow and interflow and baseflow. The simulated hydrograph is calibrated against observed discharge. From the first step, the calibrated model parameters were used to setup the smaller baseline model

The calibration routine used in NAM model is based on multi-objective optimisation strategy, where calibration can be performed to meet multiple objectives – overall water balance, overall root mean square error, peak flow root mean square error and low flow root mean square error. In this respect it is important to note that, in general, trade-offs exist between the different objectives. For instance, one may find a set of parameters that provide a very good simulation of peak flows but a poor simulation of low flows, and vice versa.

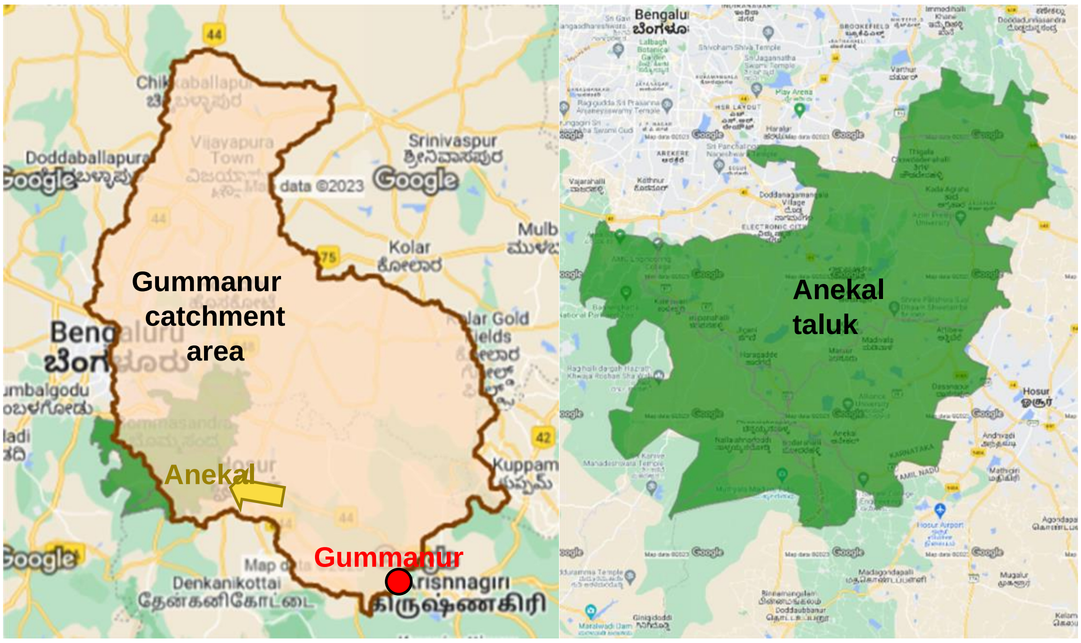


Figure 3.9 **To the right, catchment area draining to Gummanur station; to the left, the calibration parameters are transferred to the smaller Anekal baseline model shown in green colour. The red dot represents the location of gauging site**

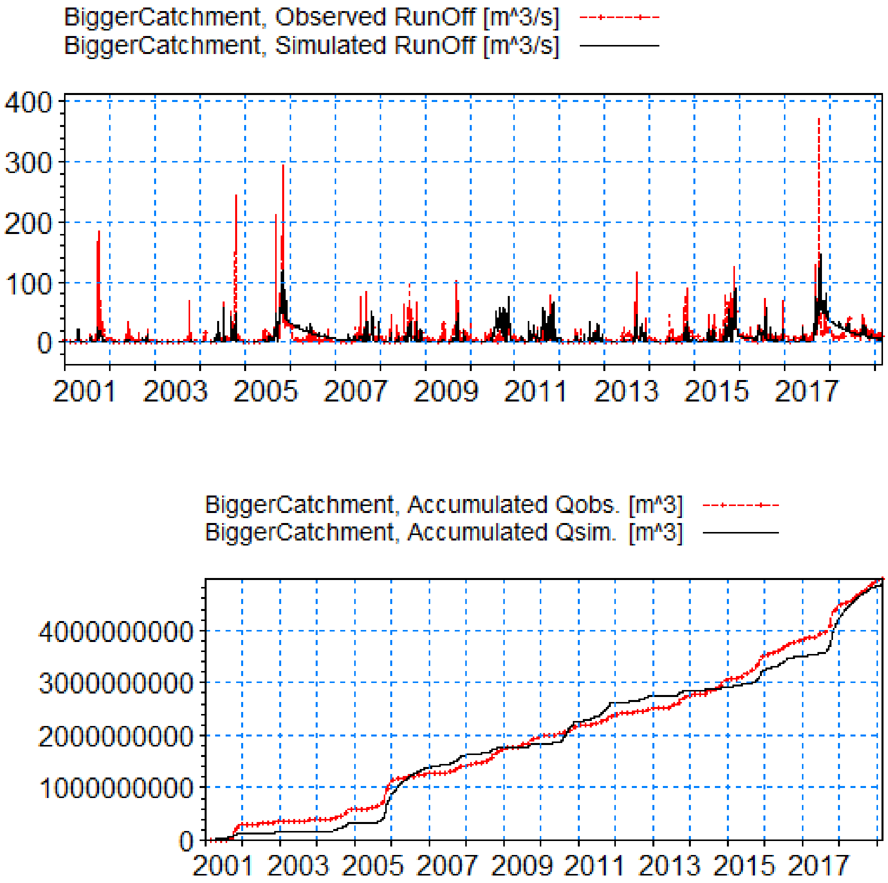
In present case, single calibration objectives were chosen to focus on the overall water balance, which is defined below:

- Overall water balance. This defines the agreement between the average simulated and observed catchment runoff, overall volume error. This is defined as

$$F1(\emptyset) = \frac{1}{N}\sum_{i=1}^{N}\left[Q_{obs,i} - Q_{sim,i}(\emptyset)\right]$$

where, $Q_{obs,i}$ is the observed discharge at time *i*
$Q_{sim,i}$ is the simulated discharge at time *i*
$\emptyset$ is the set of model parameters to be calibrated
N is the number of time steps in the calibration period

A good calibration is said to be achieved, when the model outputs agree with observations, here in this case river discharge. Both numerical as well graphical comparison should be emphasized. It is also important to understand that the objective of the calibration exercise here in this study was to reduce the water balance error. With the current set of observations (river discharge), the overall water balance error of 2.2% is achieved, which indicates the model is able to reproduce the water balance well. Figure 3.10 shows the calibration plot and the values of calibration performance measure..



Calibration performance measures
WBL = 2.22% (obs = 51.2 mm/y, sim= 50.9 mm/y)

Figure 3.10 Calibration results as plots comparing daily observed and simulated discharge (top), accumulated observed and simulated discharge (middle), and R2 and WBL performance measures (bottom).

3.2.5 Limitations

The purpose of the model is to simulate different water users at the watershed level considering the availability of water sources, to understand the impact on the state of water resources by different water uses. The approach has been centred on achieving the overall water balance by quantifying the inflows, the outflows, and changes in groundwater storage. Further below assumptions are made, which may be revised with better estimates.

- Same cropping pattern in the baseline period (2010-2020) across all the watersheds
- Population is considered to be constant in the baseline period.
- Industrial use is considered constant in the baseline period and does not change from year to year.

3.3 Future scenarios

Four future scenarios are constituted to understand the implications on the state of water resources in Anekal taluk considering the projected water uses (based on the proposed urban developments /2/ and /3/) and projected climate (based on IPCC AR6 report /19/, and /27/, /28/).

As summarized in Table 3.4 the proposed scenarios will consist of a combination of urban development and Climate Change projections. Three climate change scenarios were considered for the near future period of 2021 to 2040 in this study: 'Low' SSP1-1.9, 'Medium' SSP2-4.5 and 'High' SSP3-7.0 in reference to the level of mitigation and adaptation challenges and emissions in each. Below table describes the four future scenarios built on top of the baseline.

Table 3.4 Scenario descriptions

No.	Description
S0	Conditions in the watersheds in the baseline period from 2010 to 2021 No planned developments No climate change projections
S1	Developments inferred from LULC and available masterplans, expected to be in place by 2031 No climate change projections
S2	S1 and SSP1-1.9 climate change projections Near Future (2021-2040) 'low emissions'
S3	S1 and SSP2-4.5 climate change projections Near Future (2021-2040) 'middle of the road'
S4	S1 and SSP3-7.0 climate change projections Near Future (2021-2040), 'high emissions'

Proposed Urban Development and Climate scenarios are based on the Revised Master Anekal Plan /2/ and IPCC AR-6 reports /19/, and /27/, /28/ whereby factors expressing the change were obtained and applied to the baseline's climate and water demands.

3.3.1 Climate

The baseline climate was adjusted to represent future climate in the following way:

- Monthly delta factors for three socio-economic pathways: 1.9, 4.5 and 7.0 were calculated for time period 2021-2040.
- The baseline daily rainfall and PET time series are multiplied by the delta factors.

$$\text{Rainfall}_{1.9} = \text{Rainfall}_{\text{baseline}} * \text{Delta Factor}_{1.9}$$

$$\text{Rainfall}_{4.5} = \text{Rainfall}_{\text{baseline}} * \text{Delta Factor}_{4.5}$$

$$\text{Rainfall}_{7.0} = \text{Rainfall}_{\text{baseline}} * \text{Delta Factor}_{7.0}$$

$$\text{PET}_{1.9} = \text{PET}_{\text{baseline}} * \text{Delta Factor}_{1.9}$$

$$\text{PET}_{4.5} = \text{PET}_{\text{baseline}} * \text{Delta Factor}_{4.5}$$

$$\text{PET}_{7.0} = \text{PET}_{\text{baseline}} * \text{Delta Factor}_{7.0}$$

For more information on the climate change scenarios consult the 'Data collection and mapping report'.

3.3.2 Water demand

The baseline water demands were adjusted considering the population projections and urban developments in the decade 2031-2040. The closest credible source of information to project population in Anekal is sourced from 'Population projection of India and States' published by Census of India in 2020. In this report, state level projections were available where 18% growth is projected for Karnataka state by 2036 with respect to 2011. However, the district level and taluk level projections were not available. In the absence of such estimates, and due to lack of other credible sources, the same growth rate is considered for both Bangalore Urban District and for Anekal Taluk for calculating projected domestic water demand. For the industrial demand category, the same growth rate of 18% is considered. In the case of agricultural water demand, the land use change (see section 5.2.1) was used to project the water demand. It is estimated to correspond to 2% increase in agriculture lands in 2031.

Table 3.5 Future water use change factors

Future Water Demand	% Change with respect to baseline water demand
Domestic	+ 18%
Industrial	+ 18%
Agriculture	+ 2%

Between the baseline (S0) and all four future scenarios (S1 – S4), the water demand incurred the corresponding increase of 18% in the domestic and industrial category, with the net annual increase of ~ 819,618m^3 in domestic and 124,173 m^3 in industrial. Scenario(s) S2-S4 do not exhibits any change in the water demand when compared to S1.

For agriculture demands, the 2% annual increase resulted in approximately 702,968 m^3 or 702 thousand cubic meter (TCM) in S1-S4 compared to baseline.

3.3.3 Limitations

Though results are based on the best available information on the projected water uses and climate and a dynamic and daily water resources modelling approach, they referenced to the baseline scenario. This means assumptions and uncertainties in the baseline calculations are also carried forward in the future scenario results. The results should be read relatively with respect to baseline.

The climate change scenarios are based on assumptions about future global greenhouse gas emissions and their impact on regional climatic patterns, known as the cascade of uncertainty in climate change projections.

4 Indicator framework

Through the data and information collected during Task 2, and Task 3's modelling work results, indicators were estimated to address the proposed framework of questions by FW. The indicators are grouped into four categories 'LULC', 'water quality', 'climate' and 'water resources'. The correspondence between the indicators and the questions is presented in Table 4.1.

Table 4.1 Linkage between indicators and FW's framework of questions

#	Questions	Category	Indicator
1	What is the current total amount of water received in the selected area from all sources?	water resources	Current total amount of water available for use
2	How has the land use and land cover changed over the period 2010 - 2022?	LULC	LULC change
3	What is the current water demand in the selected area disaggregated by water use category?	water resources	Current water demand disaggregated by sector
4	What is the total amount of water available for use in the watershed?	water resources	Current total amount of water available for use
5	What is the percentage of current demand that is being met?	water resources	Current total amount of water available for use, and Current water demand disaggregated by sector
6	What is the current water storage capacity in the area?	water resources	Current total amount of water available for use, and Current water use disaggregated by sector
7	What is the available storage potential in the watershed, what percentage of future demand can it meet?	water resources	Projected total amount of water available for use, and Projected water use disaggregated by sector
8	Projections or demand scenarios of water demand sector-wise for next 10 and 20 years.	water resources	Projected water demand disaggregated by sector
9	Projections for land use and land cover changes for next 10 and 20 years.	LULC	LULC change
10	What has been the precipitation trend over the period 2010-2022, how will it change in next 10 and 20 years?	climate	Precipitation trends and projections
11	What is the temperature and relative humidity over the period 2010-2022 and how will it change in next 10 and 20 years?	climate	Temperature trends and projections
12	What is the aquifer recharge and how is it likely to change in next 10 and 20 years?	water resources	Groundwater recharge, and Groundwater Recharge Index
13	How has water quality changed over the period 2010 - 2022?	groundwater quality	Groundwater Quality Index

#	Questions	Category	Indicator
14	What are the locations of critical/stressed source of groundwater?	water resources	Critical/stressed groundwater

In addition to the indicators above, one indicator focusing on lakes was added to the 'water resources' category: lake storage volume, which is the simulated mean annual stored volume in a lake.

In the following sections, the methodologies used are described, for technical details refer to Appendix C 'Technical reference'. In the cases of LULC, water quality and climate indicators results are also presented and analysed. In the case of water resources indicators, results are presented and analysed in dedicated section 5, 'Water resources scenario analysis'.

4.1 Land use land cover indicator

Planning, utilization, and managing land resources requires comprehensive information on the geographical distribution of land use/land cover categories and the trend of their change. Information on land use helps with planning for development by enabling a better understanding of the land utilization aspects of cropping patterns, fallow areas, forests, grazing lands, waste lands, and surface water bodies. It is why FW has included in their proposed framework items 2 'How has the land use and land cover changed over the period 2010 - 2022?' and 9 'Projections for land use and land cover changes for next 10 and 20 years'.

The sections in Appendix C.1, present in detail the approach for calculation of the LULC changes, the main results are presented next.

The method applied was post-classification change detection. This method of change detection requires the comparison of independently produced classified data, which was done using a GIS environment and tools. The result of the digital image classification and visual image interpretation of the LULC available for years 2010 and 2022 was overlaid to view the LULC change and to quantify it. Here, land use and land cover maps for 2010 and 2022 shown in Figure 4.1 were used to produce change maps in Figure 4.2.

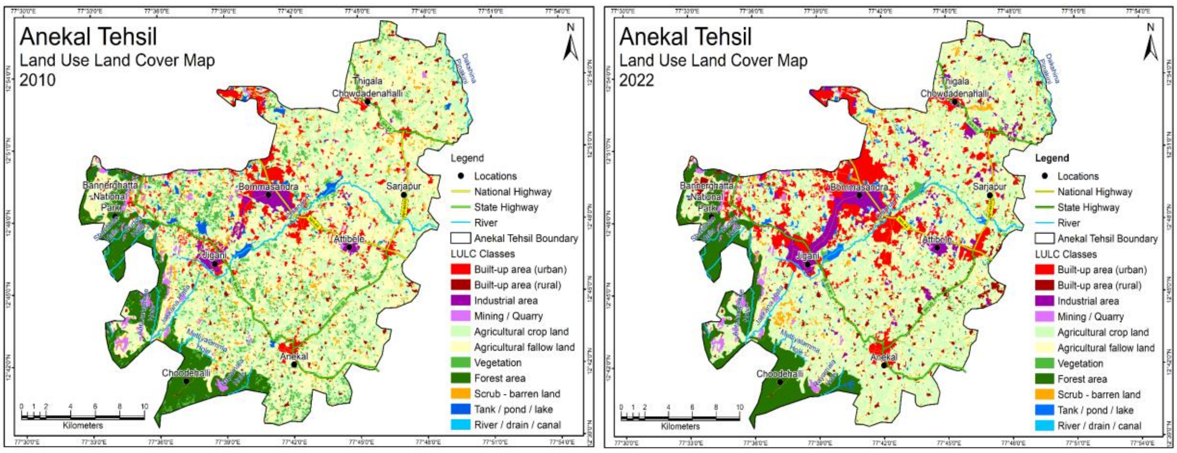


Figure 4.1 Land use and land cover map of years 2010 and 2022

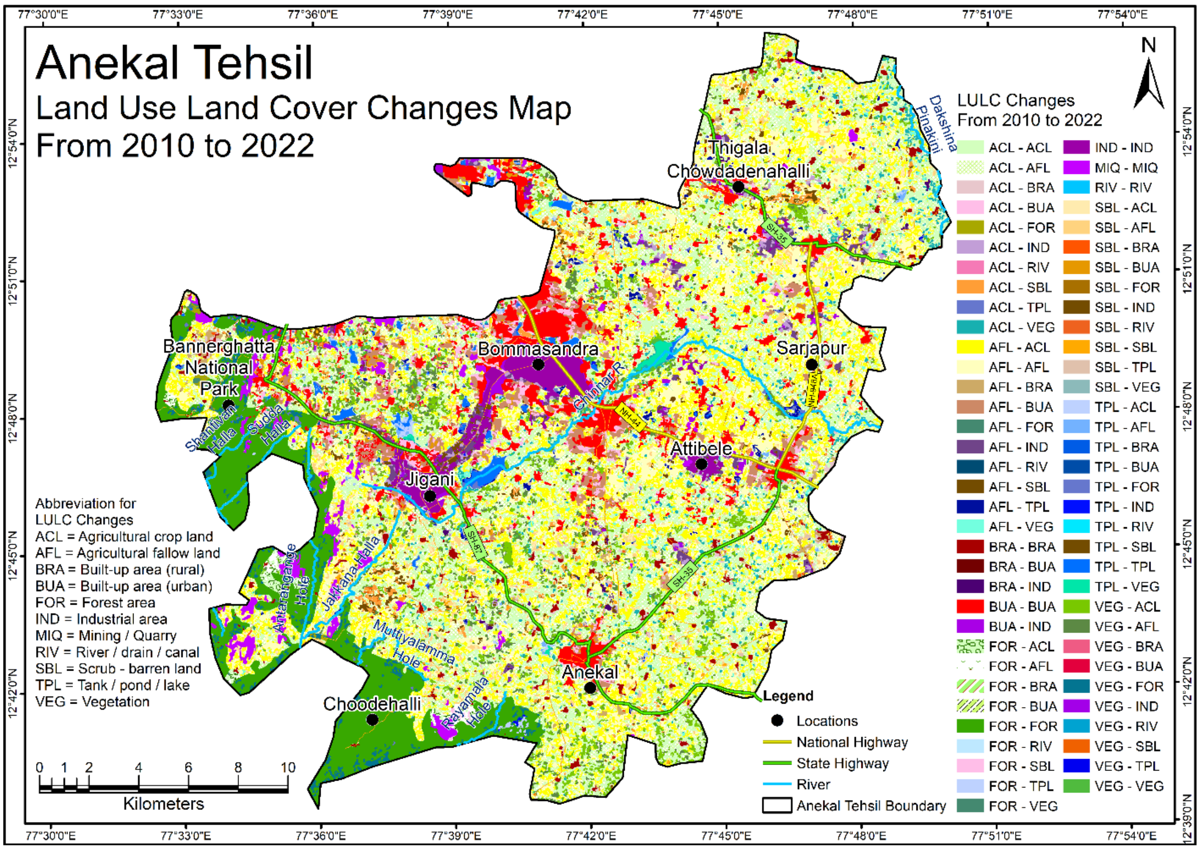


Figure 4.2 Land use and land cover changes map from 2010 to 2022

The area for each class is shown in Table 4.2 and the change results in Table 4.3. The total area of Anekal tehsil is 527.62 Km^2. As can be observed in the change map and confirmed using Table 4.3, LULC class coverage comprises mostly agricultural land at 67.23%, forest area 8.56%, vegetation 6.87%, built-up 6.77%, and scrub - barren land at 4.48% in 2010. In 2022, this changed to agricultural land 64.57% built-up 12.36%, and forest area 8.89%.

Table 4.2 Land use land cover classification for year 2010 and 2022

S. No.	LULC Classification	LULC Area (2010)		LULC Area (2022)		LULC change (difference between 2022 and 2010)		% of growth /downfall
		Km^2	%	Km^2	%	Km^2	%	
(1)	(2)	(3)	(4)	(5)	(6)	(7) = (5)-(3)	(8) = (6)-(4)	(9) = ((6)/(4)/100)
1	Built-up area (urban)	29.44	5.58	53.85	10.21	24.41	4.63	182.90
2	Built-up area (rural)	6.26	1.19	11.37	2.15	5.10	0.97	181.45
3	Industrial area	10.80	2.05	22.49	4.26	11.69	2.21	208.17
4	Mining / quarry	8.40	1.59	8.53	1.62	0.13	0.03	101.59
5	Agricultural crop land	170.48	32.31	180.57	34.22	10.09	1.91	105.92
6	Agricultural fallow land	184.27	34.92	160.10	30.34	-24.17	-4.58	86.88
7	Vegetation	36.27	6.87	11.76	2.23	-24.51	-4.65	32.42
8	Scrub - barren land	23.61	4.48	18.10	3.43	-5.52	-1.05	76.64
9	Forest area	45.16	8.56	46.88	8.89	1.72	0.33	103.81
10	Tank / pond / lake	6.71	1.27	7.43	1.41	0.73	0.14	110.82
11	River / drain / canal	6.22	1.18	6.55	1.24	0.33	0.06	105.29
	Total	527.62	100.00	527.62	100.00			

It is evident from the above table that the urban area has shown significant growth over this period, it has increased from 29.44 Km^2 to 53.85 Km^2 with 182.90% growth. Apart from urban area, other classes such as rural area, and industrial area have also shown significant development: rural area increased from 6.26 Km^2 to 11.37 Km^2 with 181.45% growth, and industrial area increased from 10.80 Km^2 to 22.49 Km^2 with 208.17% growth.

Of note is that the forest area has also increased from 45.16 Km^2 to 46.88 Km^2 with 103.81% growth. In Anekal tehsil, agricultural fallow land, and vegetation have decreased over the time (2010-2022) as 86.88%, and 32.42% respectively.

Table 4.3 Land use land cover conversion matrix in square kilometres from 2010 to 2022

Land Use / Land Cover Classes		Area (Km^2) for Year – 2022											LULC Classes wise Area for Year 2010 (Km^2)
		Built-up area (urban)	Built-up area (rural)	Industrial area	Mining / Quarry	Agricultural crop land	Agricultural fallow land	Vegetation	Scrub – barren land	Forest area	Tank / pond / lake	River / drain / canal	
Area (Km^2) for Year – 2010	Built-up area (urban)	27.47		1.97									29.44
	Built-up area (rural)	0.08	5.77	0.41									6.26
	Industrial area			10.80									10.80
	Mining / Quarry				8.40								8.40
	Agricultural crop land	9.52	2.24	3.48	0.13	81.73	59.91	6.51	5.15	0.51	1.22	0.07	170.48
	Agricultural fallow land	13.22	2.74	4.16		75.00	78.49	3.33	5.30	0.23	1.76	0.03	184.27
	Vegetation	1.16	0.14	0.38		17.17	11.42	0.76	0.66	4.30	0.26	0.02	36.27
	Scrub – barren land	2.22	0.31	1.26		4.42	7.91	0.23	6.74	0.01	0.50	0.00	23.61
	Forest area	0.08	0.15			1.41	1.30	0.11	0.21	41.55	0.29	0.06	45.16
	Tank / pond / lake	0.09	0.01	0.02		0.85	1.07	0.81	0.04	0.27	3.38	0.16	6.71
	River / drain / canal										0.02	6.20	6.22
LULC Classes wise Area for Year 2022 (Km^2)		53.85	11.37	22.49	8.53	180.57	160.10	11.76	18.10	46.88	7.43	6.55	**527.62**

The proposed land use plan map 2031 of Anekal taluk has been prepared by using published maps from Bangalore Metropolitan Region Development Authority (BMRDA) /2/ /3/. These maps are: (i) master plan 2031 for Anekal local planning area, and (ii) revised master plan for Bengaluru - 2031 (draft): volume-4. The proposed land use plan map 2031 of Anekal tehsil is shown in Figure 4.3.

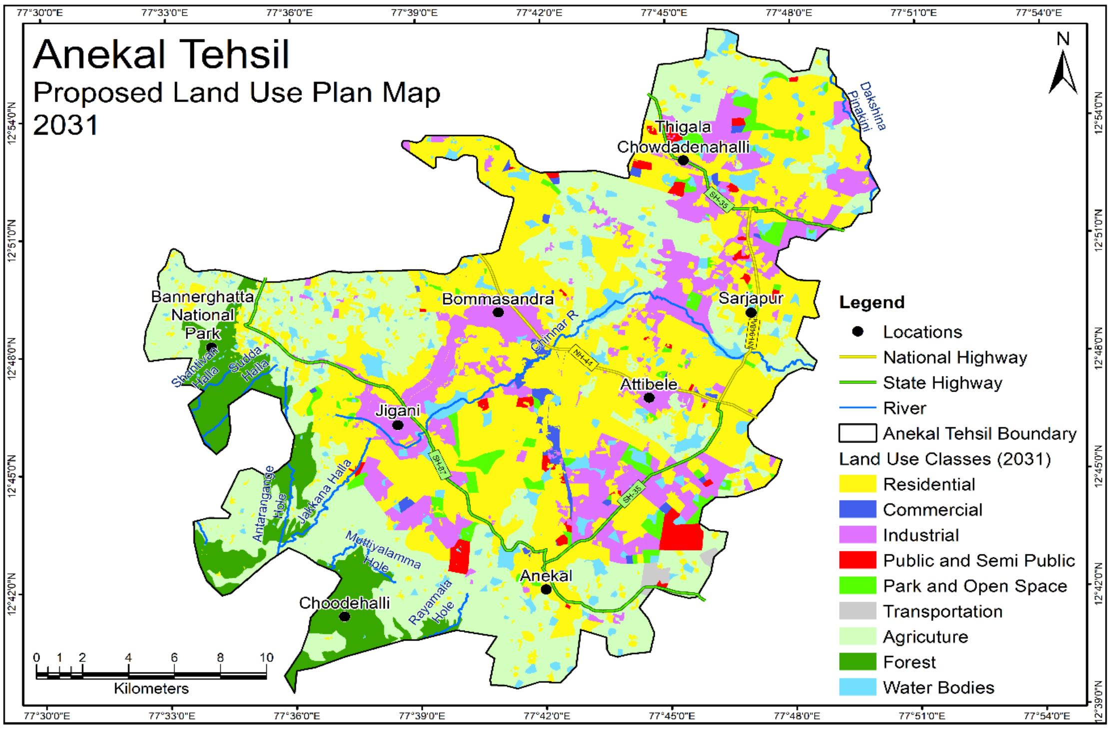


Figure 4.3 Proposed land use plan map of years 2031

To compare the past (2010), present (2022), and future (2031) land use land cover data, we have used the LULC classification and colour code from Copernicus Global Land Service (CGLS)[2], and presented in Table 4.4.

Table 4.4 Land use and land cover statistics for year 2010, 2022, and 2031

S. No.	Color Code (CGLS)	Landuse / Landcover	LULC area (km^2)			LULC area (%)		
			2010	**2022**	**2031**	**2010**	**2022**	**2031**
1	#FA0000	Urban / built up	46.51	87.70	281.70	8.82	16.62	53.39
2	#F096FF	Cultivated and managed vegetation/agriculture (cropland)	354.75	340.67	150.71	67.24	64.57	28.56
3	#FFFF4C	Herbaceous vegetation	36.27	11.76	13.56	6.87	2.23	2.57
4	#FFBB22	Shrubs	23.61	18.10	11.05	4.47	3.43	2.09
5	#B4B4B4	Bare / sparse vegetation	8.40	8.53	8.96	1.59	1.62	1.70
6	#929900	Open forest - mixed	45.16	46.88	34.79	8.56	8.89	6.59
7	#0032C8	Permanent water bodies	12.93	13.98	26.85	2.45	2.65	5.09
		Total Area (Km^2)	527.62	527.62	527.62			

4.2 Water quality indicators

4.2.1 Groundwater quality

It is acknowledged that the most important factors contributing to the deterioration of groundwater quality in India include a lack of an effective groundwater management strategy, unchecked industrial growth and waste management, rapid population growth, urbanization, municipal wastes, extensive fertilizer use, unplanned waste dumping yards, etc. (Subba Rao et al., 2018). Therefore, this features in FW proposed framework for mapping, assessing, and planning of water resources, namely question 13 'How has water quality changed over the period 2010 - 2022?'. Based on the data collected and presented in the 'Data Collection and Mapping Report' of Task 2, the approach detailed in the Appendix C.2, resulted in the calculation of a groundwater quality indicator: the groundwater quality index (GWQI).

The GWQI was calculated by the Weighted Arithmetic Water Quality Index method (WAWQI), detailed in Appendix C.2, for years 2010 and 2021, results are summarized in Table 4.5.

Table 4.5 Groundwater quality index (GWQI) for year 2010 and 2021

No.	Site Name	Groundwater Quality Index (GWQI)	
		Year-2010	Year-2021
1	Anekal	108.74	41.28
2	Attibele	57.48	59.54
3	Begihalli	42.73	45.24
4	Bhakthipur	45.27	42.19
5	CGWB Workshop	68.91	63.89
6	Haragadde	56.64	54.62
7	Jigani	114.56	64.16
8	Sarjapura	50.67	51.49
9	Singasandra	38.29	50.78

Water Quality Rating (WAWQI)	
Legend:	
>100	Unsuitable for drinking purpose
76-100	Very Poor Water Quality
51-75	Poor Water Quality
25-50	Good Water Quality

It is observed that there is an overall increasing or constant GWQI trend from 2010 to 2021 except for one location e.g. Singasandra. It can be observed that the GWQI in two groundwater monitoring well locations such as Anekal, and Jigani has superabundantly increased from unsuitable for drinking purpose to good water quality and poor water quality, respectively. It has also observed

[2] https://land.copernicus.eu/global/products/lc

that, some groundwater monitoring well locations with respect to GWQI are more-or-less constant over the years e.g.. Attibele, Begihalli, Bhakthipur, CGWB Workshop, Haragadde, and Sarjapura.

It can be seen from Figure 4.4 and Figure 4.5 that the GWQI values show large variation over the area, and as general the GWQI is increasing or constant from 2010 to 2021. Figure 4.4 of year 2010 indicates that the south part around Anekal, and Jigani have the worst values of GWQI results in comparison to the remaining part. In the north area nearby the Singasandra, GWQI went up to 38, and some isolated patches nearby Begihalli and Bhakthipur falls within the good groundwater quality category according to this index. As seen in the 2021 GWQI map (Figure 4.5), the GWQI in various groundwater monitoring well locations such as Attibele, CGWB Workshop, Haragadde, Jigani, Sarjapura, and Singasandra show poor water quality; while the areas nearby Anekal, Begihalli, and Bhakthipur show the good water quality, according to this methodology.

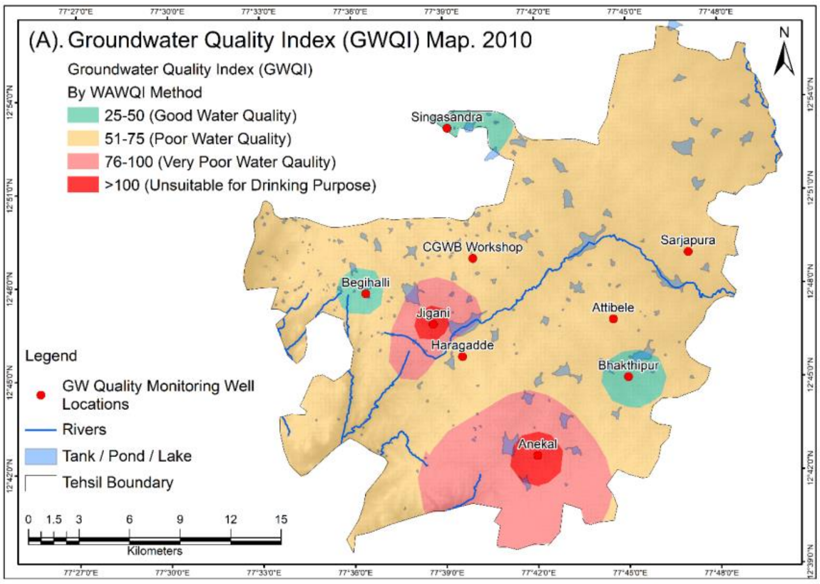


Figure 4.4 Groundwater quality index (GWQI) for year 2010

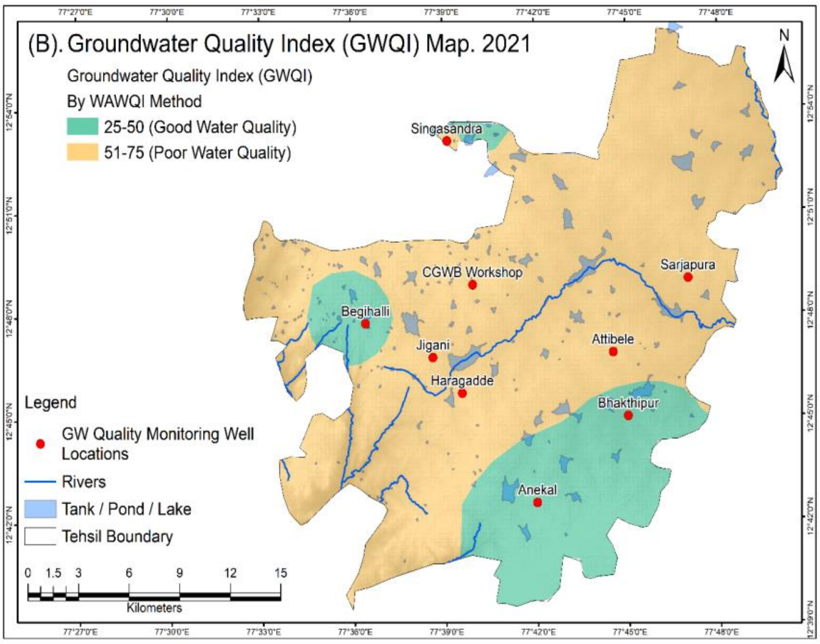


Figure 4.5 Groundwater quality index (GWQI) for year 2021

4.2.2 Surface water quality

Multispectral satellite imageries of Landsat-5 TM for year 2010; and Landsat-9 OLI-2, Sentinel-2A MSI for year 2022 have been used to estimate water quality parameter: Chlorophyll-a (Chl-a).

Chl-a is an optically active form of chlorophyll used in photosynthesis. It is one of the most studied remotely sensed water quality parameters. The majority of studies have found strongly correlated values detecting remotely sensed Chl-a in lakes, reservoirs and coastal areas using data from Landsat-1-to-3, Landsat-5, Landsat-9, Sentinel-2, and MODIS satellites (Keith et al., 2018). Successful correlations have also been found in past studies that utilized airborne remote sensing (Dekker et al., 1996). Bonansea et al., 2018 has construct a new algorithm to prove that Landsat and Sentinel sensors can be integrated and used for water quality assessment. the algorithm is:

Chlorophyll-a (Chl-a) = $110.24-0.68*(B_{GREEN})+0.76*(B_{RED})-129.30*(B_{GREEN}/B_{BLUE})-16.62*(B_{NIR}/B_{RED})$.

Where: B_{BLUE}, B_{GREEN}, B_{RED}, and B_{NIR} are the atmospherically corrected reflectance values of Landsat / Sentinel bands. Unit is µg/L.

Surface water quality with chlorophyll-a maps for year 2010 and 2022 are shown in Figure 4.6 and Figure 4.7.

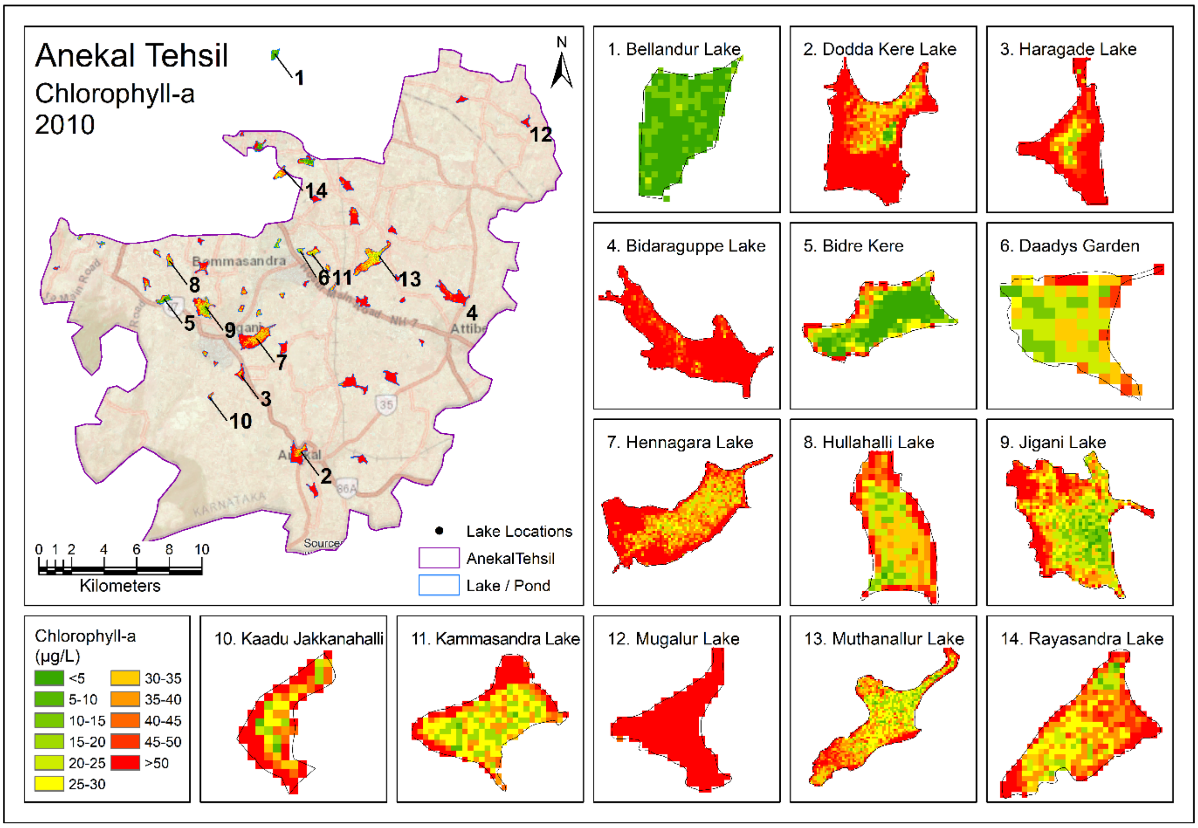


Figure 4.6 Surface water quality map with chlorophyll-a parameter of years 2010

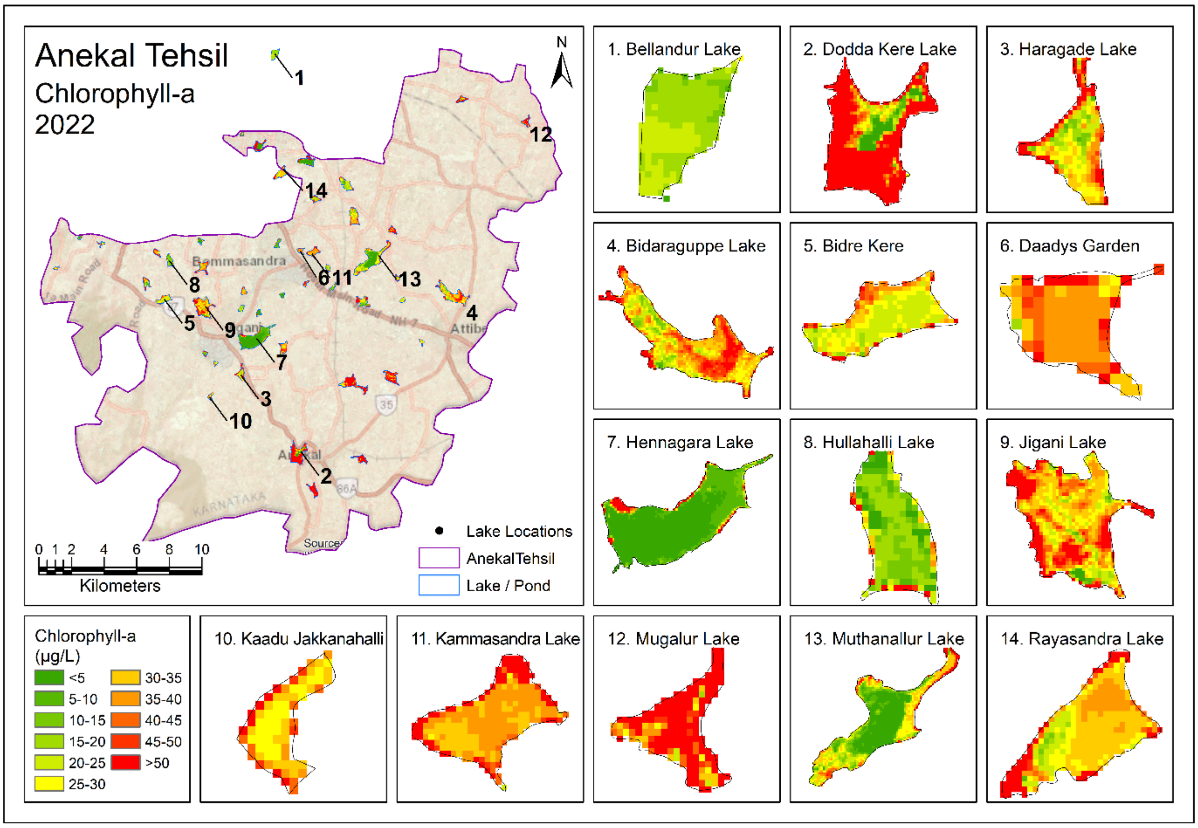


Figure 4.7 Surface water quality map with chlorophyll-a parameter of years 2022

4.3 Climate indicators

Past and future trends in precipitation and temperature can be effectively understood by observing monthly means. The indicators proposed are monthly and long-term mean precipitation and temperature on the one hand and precipitation and temperature change factors on the other hand. The change factors are an effective way to understand projections for the impacts of the IPCC climate change scenarios based on global climate models (GCMs).

Outputs from GCMs are processed into an ensemble of delta change factors for precipitation, and absolute change factors for temperature, in order to indicate projected changes in monthly mean values. The factors represent for each month the ratio (in the case of delta change factors) or the difference (in the case of absolute change factors) between the average in the historical model run (1995-2014) and the projection model run. Changes are estimated for the five socioeconomic pathways (SSPs): SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 evaluated in the IPCC AR6. The map view in the data monitor displays the median of the ensemble members.

Datasets for these two variables are available at the BtB portal and can be assessed by applying the tool ‘Time series (monthly and long term mean)’.

4.4 Water resources indicators

Table 4.6 introduces the description and calculation of each water resources indicator. The results are discussed in the scenario analysis section of this report.

Table 4.6 Description of the water resources indicators

Indicator	Unit	Description	Formula
Current water demand disaggregated by sector	m^3/s	Amount of water required in the baseline scenario by domestic, agricultural, industrial and sectors in Anekal.	Estimation is presented in section 3.2.3
Current water use disaggregated by sector	m^3/s	Simulated amount of water used by each category: domestic, agricultural, industrial in Anekal.	Total groundwater abstraction per use category from the baseline scenario
Current total amount of water available for use	Mm^3	Simulated groundwater recharge minus the natural discharges a.k.a. extractable GW resource for the baseline scenario (b)	$Tot_{GWB} = Groundwater\ Recharge_{(b)} - Groundwater\ Discharge_{(b)}$
Projected water demand disaggregated by sector	m^3/s	Amount of water required in the future scenarios by domestic, agricultural, industrial sectors in Anekal.	Current demand multiplied by factors: Domestic 18%, Agriculture 2%, Industrial 18% and as presented in section 3.3.2
Projected water use disaggregated by sector	m^3/s	Simulated amount of water used by each category: domestic, agricultural, industrial in Anekal.	Total groundwater abstraction per use category from the future scenarios S1 to S4
Projected total amount of water available for use	Mm^3	Simulated groundwater recharge minus the natural discharges a.k.a. extractable GW resource for the future scenarios S1 to S4 (p)	$Tot_{GWP} = Groundwater\ Recharge_{(p)} - Groundwater\ Discharge_{(p)}$
Groundwater Recharge Index	%	This is an index describing the groundwater recharge as a percentage of the recharge in the baseline scenario.	$R\_Si = \frac{RSi}{RBase} \times 100$
Critical/stressed groundwater	%	This is the same formulation as used in their official reporting by the District Groundwater Office, Groundwater Directorate, and the Central Ground Water Board, South Western Region, Bangalore. Stage of Extraction (SoE) is the percentage of utilisation with respect to annual extractable ground water resources. The Annual Extractable Ground Water Resource (EGR) is computed by deducting the Total Annual Natural Discharge from Total Annual Ground Water Recharge (CGWB, 2022 (p.37))	$SoE = \frac{Annual\ Extraction\ by\ all\ U}{Annual\ EGR}$ Classification: Safe: SoE < 70 % Semi-critical: 70 < SoE <= 90 % Critical: 90 < SoE <=100 % Over-exploited: SoE > 100 %
Lake storage volume	Mm^3	Simulated mean annual stored volume	

5 Water resources scenario analysis

This chapter analyses the status of water resources in Anekal taluk by using the indicators to compare across the different scenarios. The indicators were calculated using the results from the simulations ran, whereby the baseline scenario time period is from 2010 to 2021 and the future scenarios time period is from 2021 to 2040.

5.1 Current and Projected Water Use

Based on the population data, and daily per capita demand, the domestic water demand has been computed aided by surveyed information. The domestic use obtained from the model simulation for baseline and future scenarios is presented in Figure 5.1. Annual water use of 4,254,030 m^3 in baseline and 5,019,755 m^3 in future scenarios is estimated. Rather than transferring Bengaluru city's growth rates, this approximation was made in a simplified manner in light of the lack of taluk specific data and other assumptions in the modelling to establish the representation of this use which is not the major use in the system (<10%). Further, the computed water demand does not show much sensitivity towards domestic demand growth rate i.e. changing projected growth factor from 18% to 40% resulted in 0.02% rise in total water demand (~1 mcm). Thus, 18% population growth rate was kept for modelling purpose.

The industrial use obtained for the baseline and all four future scenarios is shown in Figure 5.2. Annual water use of in industrial category is estimated to be 644,490 m^3 in baseline and 760,499 m^3 in all future scenarios.

The agriculture water use estimated for the baseline and all four future scenarios is shown in Figure 5.3. The water use varies annually in the range of 31,091,858 m^3 to 49,925,517 m^3 in the baseline scenario. The range is likely to increase from 31,713,695 m^3 to 50,924,028 m^3 in future scenarios.

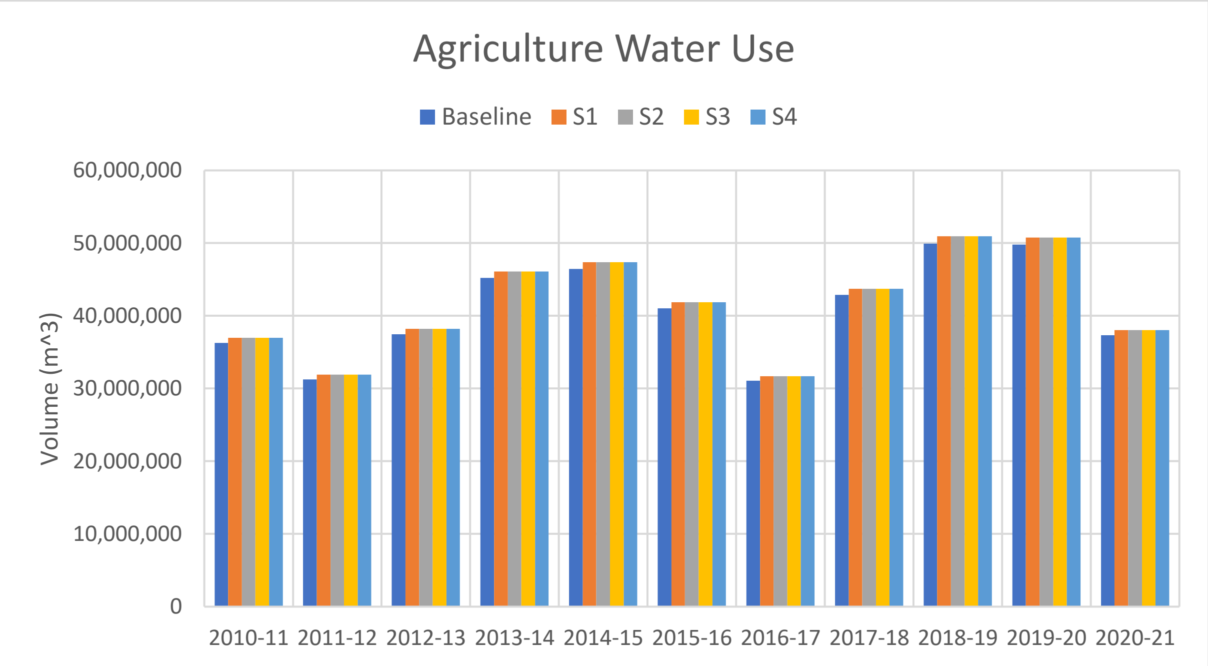


Figure 5.1 Agriculture water use of Anekal taluk for baseline and future scenarios

5.2 Current and projected total amount of water available for use

This indicator is based on the definition of 'annual extractable groundwater resource' by CGWB which indicates the amount of groundwater available in a year for use. We define this as 'Total Groundwater Availability' and it is estimated based on two model outputs: groundwater recharge and groundwater discharge. The formula for calculating this indicator is:

$$Total\ GW\ Availability \quad = Annual\ Recharge - Annual\ discharge$$

where,

$Annual\ Recharge$ is the total amount of recharge simulated in a hydrological year, in m^3
$Annual\ Discharge$ is the total amount of natural groundwater discharged in a hydrological year, in m^3

Figure 5.2 below shows the values simulated for the baseline period and four future scenarios. It is shown how groundwater availability varies annually and is a function of rainfall. In high rainfall years such as 2017-18, 2015-16 the availability is high compared to the other years. The range with respect to baseline conditions, varies in between -23% to 14%, -54% to 19% and -5% to 58% in the scenarios S2, S3 and S4 respectively. Scenario S1 does not show any change with respect to baseline, this is because the climate is not altered.

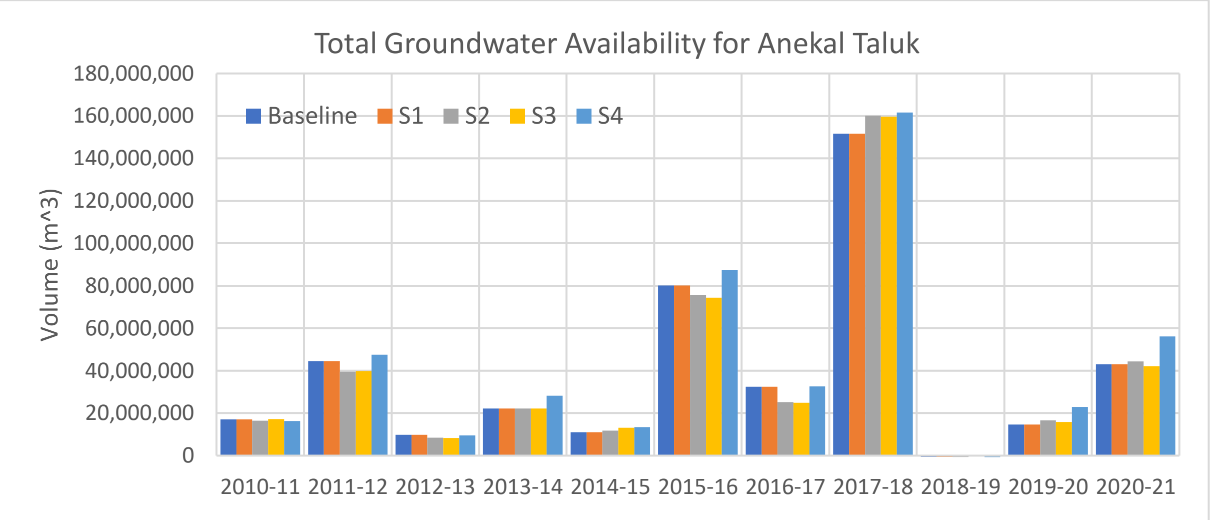


Figure 5.2 Total groundwater availability of Anekal taluk in baseline and future scenarios

5.3 Groundwater Recharge Index

This indicator is a relative indicator to describe estimated groundwater recharge across scenarios. It is calculated based on the ratio of estimate recharge in a future scenario with respect to baseline recharge. Groundwater Recharge Index (GRI) is calculated using below formula:

$$GRI_{sc} = \left({}^{Groundwater\ recharge_{sc}}/_{Groundwater\ recharge_{baseline}}\right) \times 100$$

where,

GRI_{sc} is the Groundwater recharge index of a future scenario e.g. S1, S2, S3, S4
$Groundwater\ recharge_{sc}$ is the groundwater recharge of a future scenario
$Groundwater\ recharge_{baseline}$ is the groundwater recharge of baseline scenario

GRI is calculated for all the four future scenarios, S1-S4. Figure 5.3 shows the computed GRI for all future scenarios. GRI ranges from 78% to 115%, 77% to 138% and 95% to 159% for the scenarios S2, S3 and S4 respectively. To better understand this indicator, it is important to understand the recharge for each scenario. Please see Figure 5.4 for estimated recharge under each scenario including baseline. As clearly seen, recharge is high in high rainfall year and so is the relative change across scenarios.

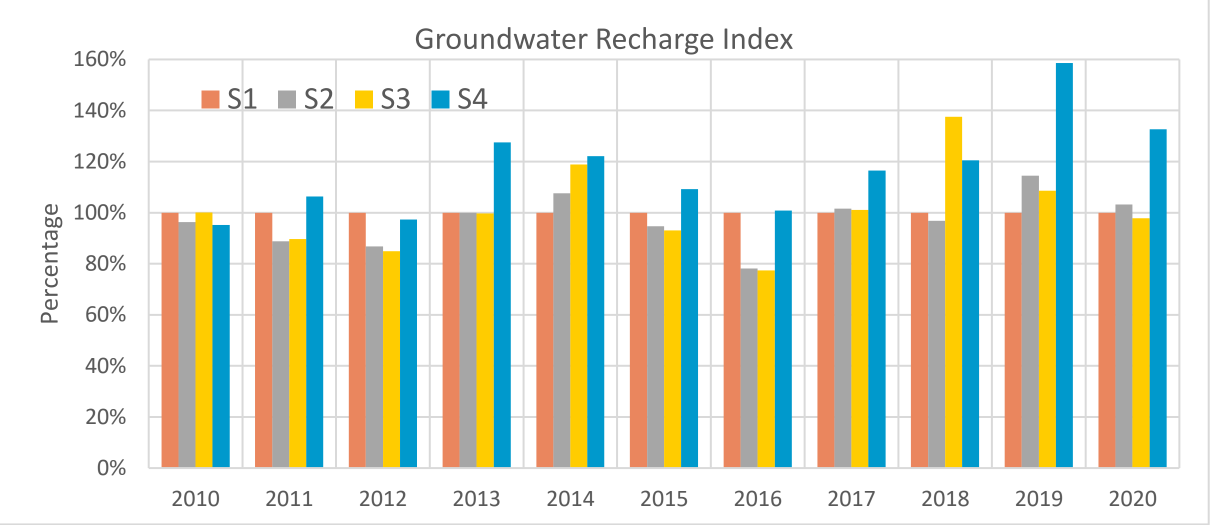


Figure 5.3 Groundwater Recharge Index of Anekal taluk in baseline and future scenarios

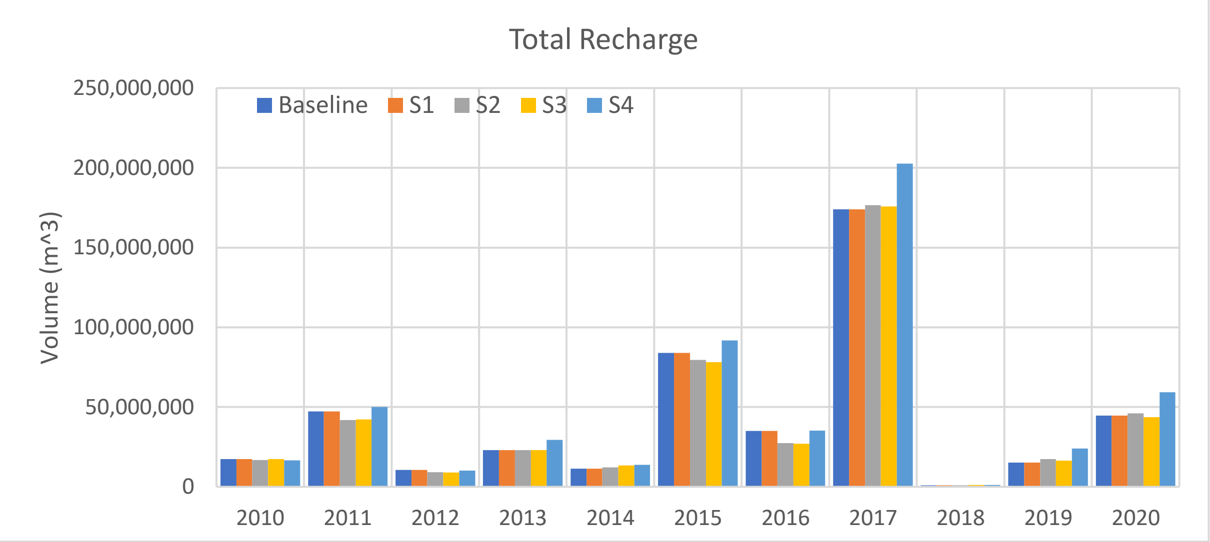


Figure 5.4 Simulated groundwater recharge of Anekal taluk for baseline and future scenarios.

5.4 Critical/stressed groundwater

This indicator is of a relative nature and is used to describe the stage of extraction and potential stress level imposed on the groundwater resource. It is used by Karnataka authorities to monitor groundwater. Following the CGWB definition, this indicator is the ratio of annual abstraction to the total annual extractable groundwater or annual groundwater availability and calculated values are categorised as follows: Safe (<70%), Semi-critical (>70% and <=90%), Critical (>90% and <=100%)and Over-exploited (>100%) classes. Following this criterion, the total abstraction (sum of domestic, industrial and agriculture use) and total groundwater availability is used to calculate this indicator.

Table 5.1 below presents the results of this indicator for Anekal taluk. They indicate that the majority of the year in all future as well as baseline scenario falls within the 'Over-exploited' category except for high rainfall years where the status changes to 'Safe'.

Table 5.1 Critical / stressed groundwater in Anekal for baseline and future scenarios

Year	Baseline	S1	S2	S3	S4
2010-11	Over-exploited	Over-exploited	Over-exploited	Over-exploited	Over-exploited
2011-12	Semi-critical	Semi-critical	Critical	Critical	Semi-critical
2012-13	Over-exploited	Over-exploited	Over-exploited	Over-exploited	Over-exploited
2013-14	Over-exploited	Over-exploited	Over-exploited	Over-exploited	Over-exploited
2014-15	Over-exploited	Over-exploited	Over-exploited	Over-exploited	Over-exploited
2015-16	Safe	Safe	Safe	Safe	Safe
2016-17	Over-exploited	Over-exploited	Over-exploited	Over-exploited	Over-exploited
2017-18	Safe	Safe	Safe	Safe	Safe
2018-19	Over-exploited	Over-exploited	Over-exploited	Over-exploited	Over-exploited
2019-20	Over-exploited	Over-exploited	Over-exploited	Over-exploited	Over-exploited
2020-21	Critical	Over-exploited	Critical	Over-exploited	Semi-critical

Since the definition of indicator is based on definitions in CGWB assessment reports, the 'categories' were compared with categories mentioned in the CGWB reports. The indicator results are well aligned with CGWB reported categories of Over-exploited in 2010-11, 2016-17 and 2019-20 respectively.

5.5 Lake storage volume

Two lakes namely, 'Doddakere' and 'Haragade', has been included in the baseline model to simulate the hydrological behaviour of the surface water source in Anekal taluk as an example. The objective of this exercise is to quantify the storage change of a lake using the model as it simulates a lake's area, depth and volume over time. This allows the assessment of the impact of a potential water use. Below section present the results for the Doddakere lake.

Figure 5.7 and Figure 5.8 show the annual mean surface area and annual mean stored volume in the Doddakere lake simulated for the baseline period. The lake receives inflows from watershed runoff and from direct precipitation. The losses include the evaporation losses, seepage to groundwater and outflows at a threshold level of 2 m should these occur.

The maximum lake area was calculated to be 382,000 m^2 with total volume of 355,000 m^3. It is observed from the results that the lakes start to fill-in with onset of monsoon and attains maximum capacity until end of the monsoon period. Thereafter, due to evaporation and seepage losses, the depth reduces, and water spread area shrinks to minimum in lean period. The inter-annual variation is also observed in between dry and wet years for e.g. from year 2012 to 2014 the annual mean stored volume reduced until year 2015, which was the high rainfall year.

The stored volume indicates potential to be used as a water-use. For a demonstrative example, the maximum annual mean volume of 185,000 cubic meter (in year 2021) would correspond to meet a daily domestic demand of 1.2 million persons. The minimum annual mean volume of 61,000 cubic (in year 2014) meter correspond to meet daily domestic demand of 0.41 million persons. This is just an example to related stored volume in lake to calculated demand in domestic category.

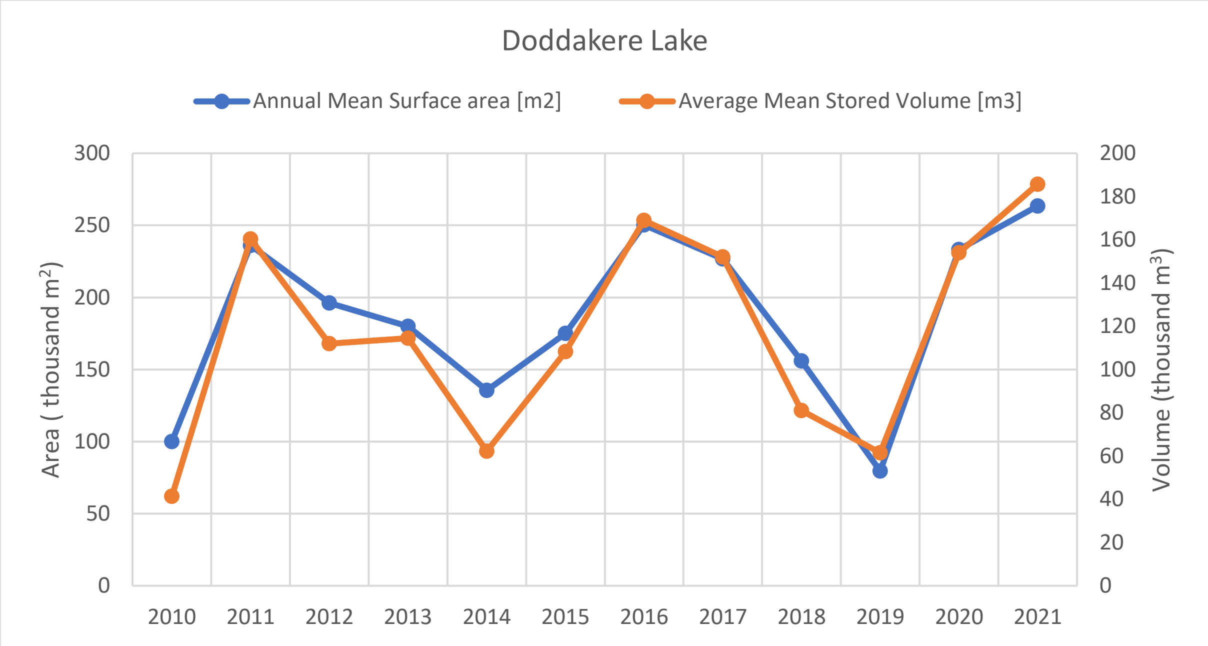


Figure 5.5 **Simulated annual mean surface area and stored volume in Doddakere lake in Anekal taluk in the baseline period**

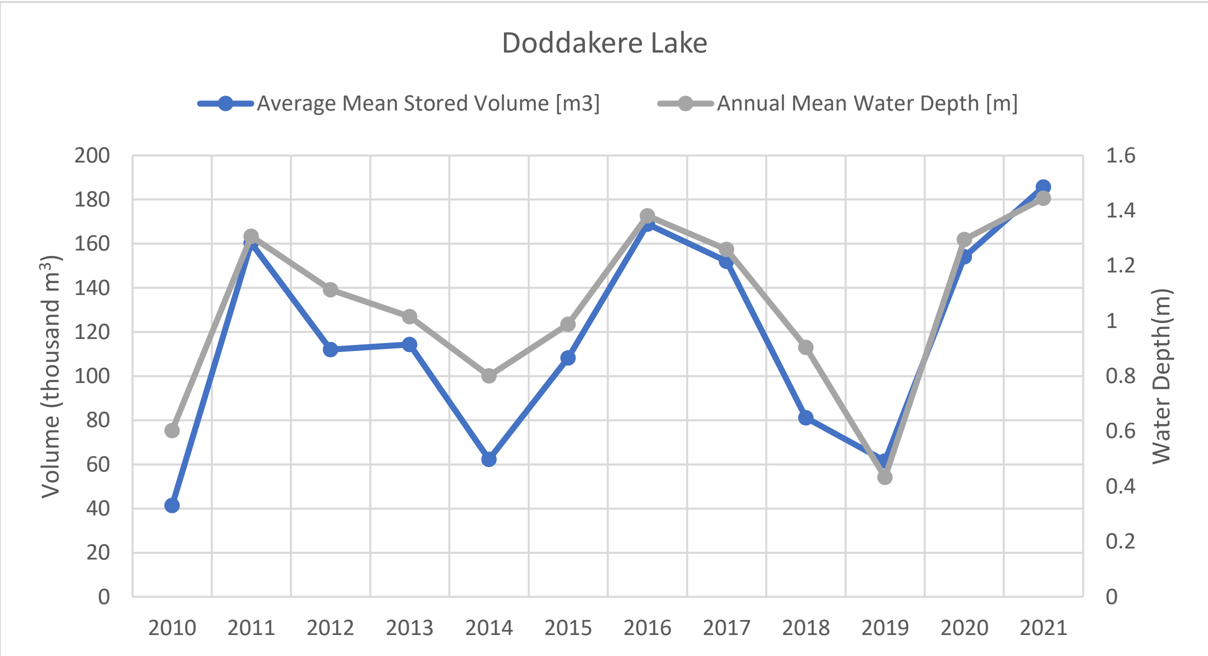


Figure 5.6 **Simulated annual mean surface area and annual mean water depth in Doddakere lake in Anekal taluk in the baseline period**

6 Conclusions and recommendations

The present study demonstrates how an indicator framework can be estimated using a watershed modelling approach and remote sending data to assess the state of water resources in Anekal taluk. Groundwater being the major source of supply to most of the users in Anekal taluk, sustainable development and management of this resource is key to ensure access for local communities, productive industries, and a healthy environment. Therefore, focus was placed on assessing the status of groundwater resources at the watershed level.

This section gathers the conclusions of this assignment with respect to the original questions proposed by FW and recommendations made for future studies.

Conclusions

Through the modelling exercise, it was observed that during dry years, when there is less rainfall, less recharge is generated which puts the taluk's groundwater under stress. The groundwater storage declines. But in high rainfall years, typically more than rainfall of 800 mm of annual rainfall, the watersheds receive relatively sufficient recharge, having a stabilizing and replenishing effect on storage.

In the long run, it is important to have sustainable water use and resource management in the taluk. If use is unsustainable, the shallow dug wells may run out of water impacting local livelihoods, a situation that has occurred in the past and is being ameliorated with mitigation measures supported by FW's partners such as MYRADA and community percolation tanks. In the near future, based on the projections, the groundwater availability is likely to reduce, thus more judicious planning is recommended.

Regarding groundwater quality, the results presented in this study are inconclusive, due to the lack of data. They were reported to demonstrate how a quality indicator could be estimated and used, should the input data be sound enough to support the analysis.

What is the current total amount of water received in the selected area from all sources?

This question can be best answered through the water resource indicator *'Total amount of water available for use'* for the baseline period. The indicator reflects on the annual extractable groundwater resource which is defined as the difference of annual natural recharge from annual natural discharge. The baseline time-period presents the good example of hydrological variability in the region, witnessed by both wet (above average rainfall) and dry (below average rainfall) years. The dynamics changes from year to year depending majorly upon the rainfall conditions.

The total amount of water received annually in Anekal taluk as simulated by the model (for 11 hydrological years from 2010 to 2021) is **43 million cubic meter (mcm)** per year on an average.

The results are discussed in section 5.1 and is available in the BtB portal.

How has the land use and land cover changed over the period 2010 - 2022?

Using indicator LULC change, detailed in section 4.1, the classes with increased area from 2010 to 2022 were 'Urban / built up' from 8.82% to 16.62%, 'Bare/sparse vegetation' from 1.59% to 1.62%, 'Open forest – mixed' from 8.56% to 6.59% and 'Permanent water bodies' from 2.45% to 2.65%. This change was at the expense of decreases in 'Cultivated and managed vegetation/ agriculture (cropland)' 67.24% to 64.57%, 'Herbaceous vegetation' 6.87% to 2.23% and 'Shrubs' 4.47% to 3.43%.

What is the current water demand in the selected area disaggregated by water use category?

This question can be described by the water resource indicator '*water demand disaggregated by sector*'. There are three major sectors or categories identified for the water use in Anekal – Domestic, Industrial and Agriculture.

- The current water demand for ‘Domestic’ category water user in Anekal taluk is **4.26 mcm** per year on average.
- The current water demand for ‘Industrial’ category water user in Aneka taluk is **0.65 mcm** per year on average.
- The current water demand for ‘Agriculture’ category water user in Aneka taluk is **41 mcm** per year on average.

What is the total amount of water available for use in the watershed?

This question can be best answered through the water resource indicator *‘Total amount of water available for use’* for the baseline period. The indicator reflects on the annual extractable groundwater resource which is defined as the difference of annual natural recharge from annual natural discharge. The baseline time-period presents the good example of hydrological variability in the region, witnessed by both wet (above average rainfall) and dry (below average rainfall) years. The dynamics changes from year to year depending majorly upon the rainfall conditions.

The indicator does not include water availability in open lakes, ponds, and small surface depressions. The present study focuses only on the groundwater dynamics and availability.

The total amount of water available for use in Anekal taluk as simulated by the model (for 11 hydrological years from 2010 to 2021) is **43 mcm** per year on an average.

What is the percentage of current demand that is being met?

The total demand of all the three major categorical water users – Domestic, Industrial and Agriculture is **46 mcm**. The net amount of water available for use, as explained in above sections, is **43 mcm** per year on an average. Thus, about **93%** of the current demand is being met.

What is the current water storage capacity in the area?

This could be best described by the two water-resource indicators – Current total amount of water available for use, and Current water demand disaggregated by sector.

The current water storage capacity simulated based on the above indicator varies in the range of 10 mcm (in dry year) to 151 mcm (in high rainfall year) per year on an average in Anekal taluk. .

What is the available storage potential in the watershed, what percentage of future demand can it meet?

This is best understood by the two water-resource indicators – Projected total amount of water available for use, and Projected water use disaggregated by sector.

The total projected amount of water available for use in Anekal taluk for the climate change scenarios (S2-S4) is expected to vary during high and low rainfall years depending on the scenarios (low or high). The projected water demand disaggregated by sector is calculated to vary in the range of 2% to 18% depending upon the category of the water use compared to baseline period.

Based on the discussions so far, Anekal taluk would be able to meet 93% its current water demands. In future scenario S1, S2 and S3, about 90% the future demands will be met while for S4 scenario, 99% of future demand is expected to be met.

Projections or demand scenarios of water demand sector-wise for next 10 and 20 years.

The projections for the water demand by 2036 are calculated based on the population projections, and relative urban developmental changes from 2010 to 2021.

- The domestic water demand is going to increase by 18% i.e., from **4.26 mcm/yr** to **5.03 mcm/yr**.
- The industrial water demand is going to increase by 18% i.e., from **0.65 mcm/yr** to **0.77 mcm/yr**.

- The agriculture water demand is going to increase by 2% i.e., from **41 mcm/yr** to **42 mcm/yr.**

Projections for land use and land cover changes for next 10 and 20 years

As detailed in section 4.1, the LULC change indicator is estimated using satellite imagery for past years. To assess projected change the official 2031 masterplan for Anekal was the utilized source, and not knowing to what degree of implementation the plan and no mechanism to monitor it available to the project team the biggest limitation. The projections for land use changes estimated are therefore for the next 10 years. In sum, the expansion of 'Urban / built up' from 8.82% in 2012 to 53.39% of the total area is the most significant change alongside a corresponding decrease in 'Cultivated and managed vegetation/ agriculture (cropland)', having gone from 67.24% in 2010 to 28.56% according to the 2031 plan. Using the portal and its tools, it is possible for stakeholders to get an overview by using the chart tool, see demonstration in Figure 6.1.

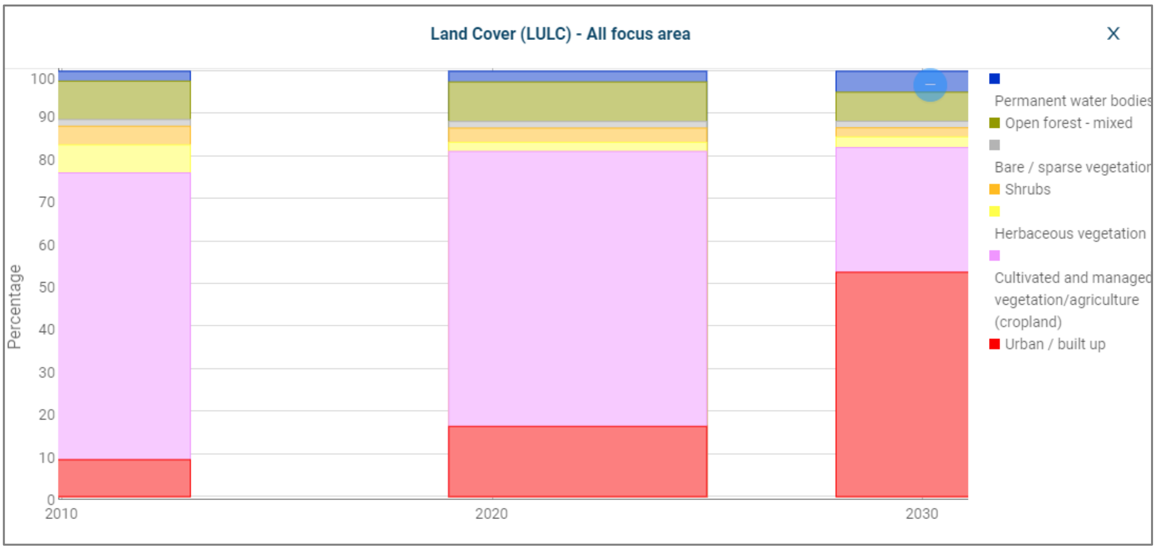


Figure 6.1 Percentage area per LULC class over time. First two instances are based on satellite observations, the last is based on the official zoning masterplan by the government authorities.

What has been the precipitation trend over the period 2010-2022, how will it change in next 10 and 20 years?

Based on the IMD gridded dataset for the time period 2010-2022, Anekal taluk received an average annual rainfall of 850 mm. The area receives early monsoon showers in month of May. The overall trend has been on the rise for the decade 2010-2022, where 5 out 12 years received above average rainfall.

However, to develop more understanding on the historical trend of rainfall, it is advised to use long-term rainfall datasets such as CHIRPS dataset available at BtB portal.

The three climate change scenarios – Low emission (S2), Moderate emission (S3) and High emission (S4), considered in the present study covers the time period 2021-2040 and presents median of the change factors. These change factors inform on the likelihood of the relative change in rainfall (for each scenario) compared to the baseline.

The monthly delta factors for the rainfall as used under three scenarios is presented below in the figure. It can be inferred that the monthly variability is high in the high emission scenario - S4 compared to other two climate change scenario.

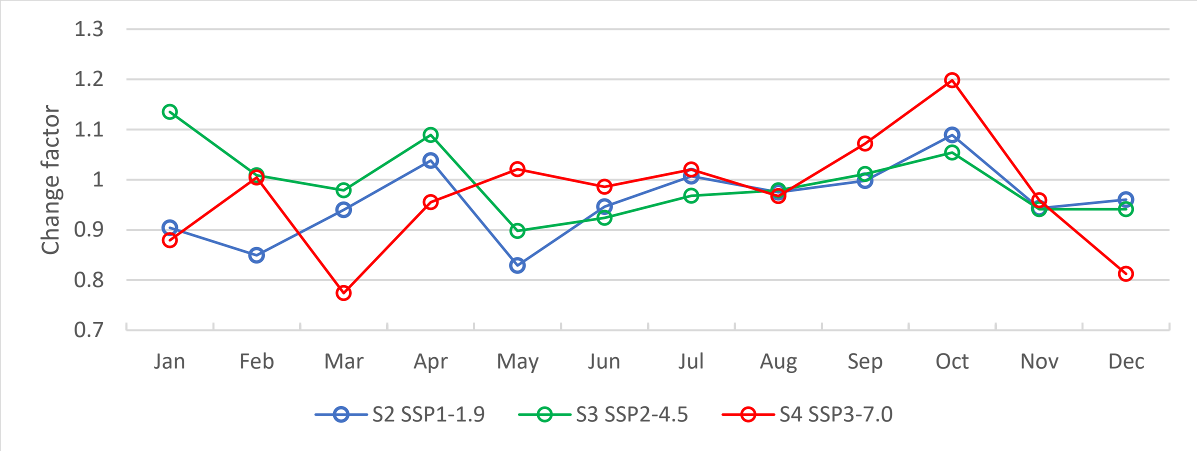
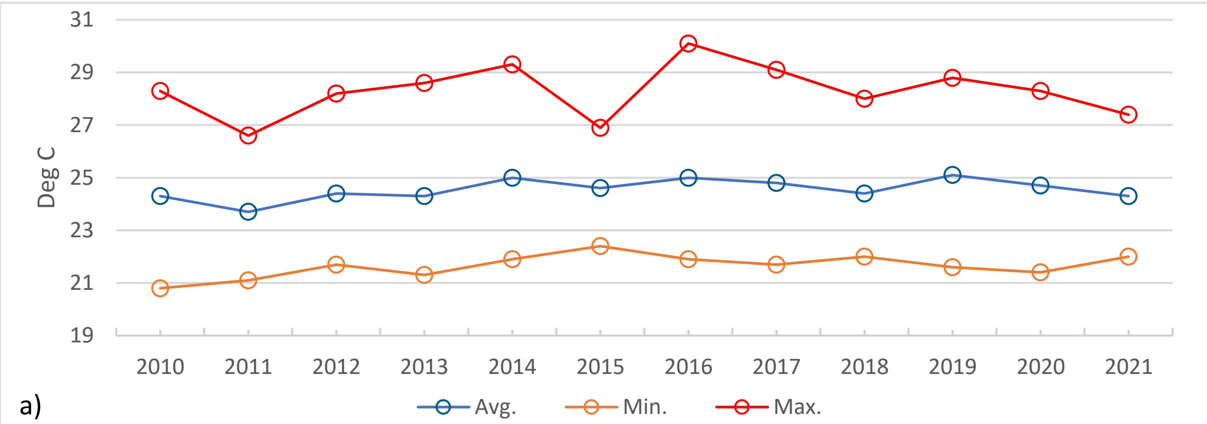


Figure 6.2 **Global monthly change factors for precipitation for Anekal, showing the projected monthly variation for three climate change scenarios depicting socioeconomic and carbon emission pathways of different likelihood.**

What is the temperature and relative humidity over the period 2010-2022 and how will it change in next 10 and 20 years?

The temperature trend for the time period 2010-2022 in Anekal taluk is presented below in the Figure 6.3 (a). This information is sourced from ERA5 Temperature global dataset available at BtB portal. The temperature projections for the Anekal taluk in the future scenarios S2 to S4 is shown in Figure 6.3 (b).



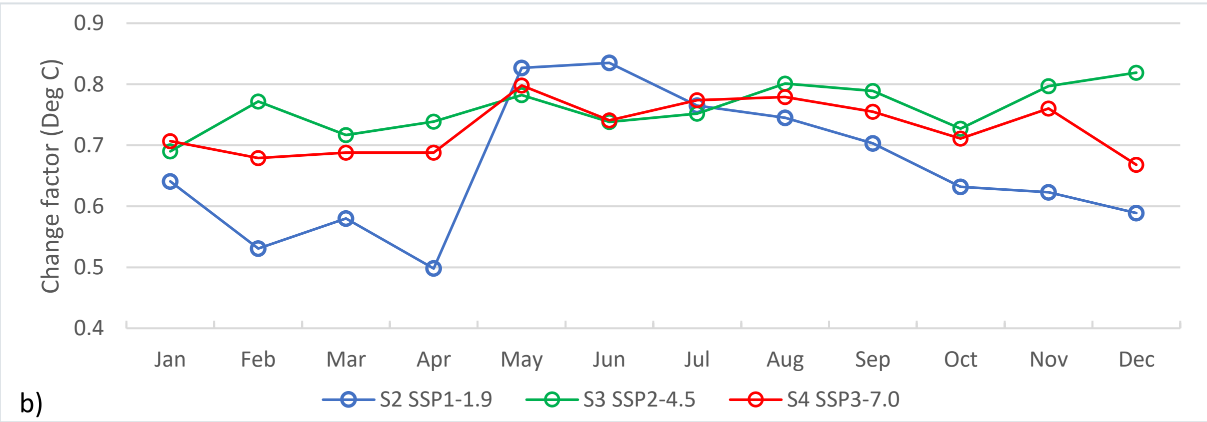


Figure 6.3 **a) Annual average temperature in Anekal taluk (Source: ERA5 Reanalysis dataset) b) Change factors for temperature in three climate change scenarios (Source: IPCC AR6 Report)**

What is the aquifer recharge and how is it likely to change in next 10 and 20 years?

The simulated aquifer recharge can be best described by two water-resource indicators – groundwater recharge and groundwater recharge index.

The aquifer recharge or groundwater recharge as estimated by the model on an average is **43 mcm** per year and can go up to **150** mcm per year in high rainfall years.

Groundwater recharge index reflects on the percentage change of the groundwater recharge with respect to the baseline The relative change is maximum for high emission scenario S4 aka SSP3-7.0 where recharge is expected to increase by 17% due to high variability in monsoon months. For other scenarios, the relative change is minimal and falls in the range of 0 to 3% for S1 and S2 scenarios respectively.

How has water quality changed over the period 2010 – 2022?

Due to the lack of available data that is consistent in time, it was not possible to respond to the question when it comes to groundwater. As a part of the demonstration, a possible groundwater quality indicator was proposed, and its calculation included in Appendix C.2. Focus for this question was on groundwater throughout the assignment. Towards the end it was decided to look at lakes in Anekal, therefore the project team sought for (within the available time) an indicator that could support assessing water quality of surface water bodies.

What are the locations of critical/stressed source of groundwater?

This could be described by the water resource indicator Critical / stressed groundwater. The indicator is defined using CGWB definition of stress which is ratio of annual abstraction to annual recharge (after deducting natural discharge). The present indicator is in itself offering more resolution where the stress level is estimated monthly.

There are in total 9 watersheds delineated for the present pilot assignment. It is inferred that the watersheds in the east – C6, C7 – and in south-southeast – C2, C3, C4 exhibits more stress than the other watersheds. The primary reason is that relative area under agriculture to the watershed area is high in these watersheds and has high agriculture water demands. The stress level is highly dependent on the recharge which is related to the amount of rainfall received in the area. The results on a monthly time scale are available on the BtB portal (see example in Figure 6.4).

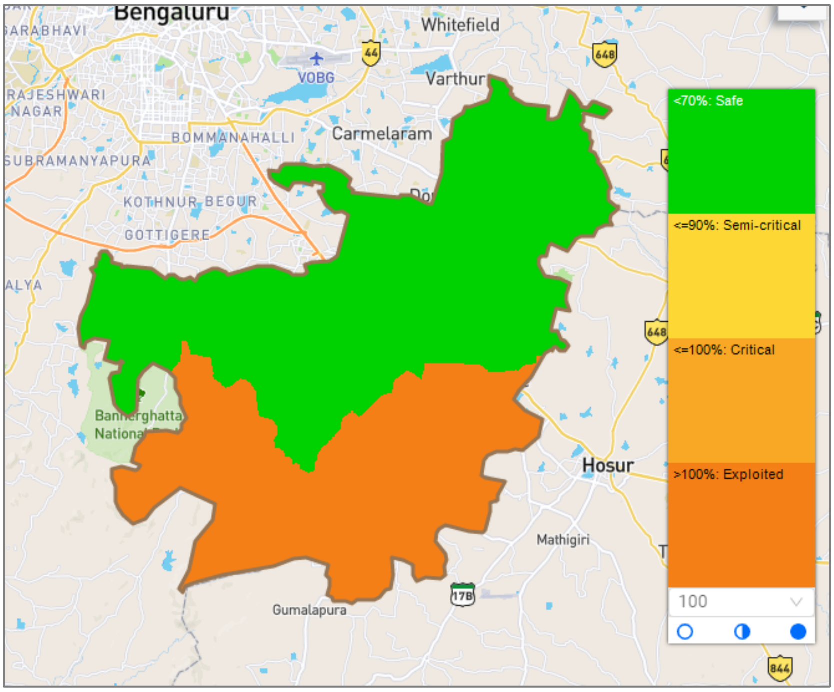


Figure 6.4 Snapshot of the Critical / stressed groundwater indicator mapped using the BtB portal showing the status at the watershed level in May 2021

Recommendations

This assignment constituted a demonstration, of how modelling and digital mapping technology can be used to support sustainable management of water resources at the watershed level. Regarding a follow up phase to move from a demonstration to the possible assimilation of such approaches, it is recommended a review of the intended users is carried out. This was a conclusion expressed by FW after the technical workshop, with user types brought up within the following a) people on the ground such as NGO staff, frontline staff of government departments, facility managers and staff of businesses etc., b) policymakers, and c) researchers and academics engaged in science and technology or advisory. User stories and use cases would be drawn based on an appraisal of decisions and needs to be supported for each case.

It is recommended that in a follow up phase of the BtB project, socio-economic, institutional and policy dimensions and specific outputs are added to the demonstration. These aspects are an integral part of water resources management and planning. The expression of this may take different forms depending on the objectives of the next phase: at the high level, acceptance and even vetting of the outputs by local government can be promoted, whereby at the technical level, indicators pertaining to these categories can be added to the water resources management framework.

Having institutional and policy expertise would allow much needed exchanges at high and technical levels with mandated watershed management authorities. These could benefit the project greatly, in terms of the methodologies applied to the improvement of data availability for its application. Direct linkages with the regulatory framework and the model outputs can be derived and could result in a strengthened backing of conclusions drawn by models built upon local communities' needs.

In addition, after the field visit, it can be concluded that models can be used to support the work of NGOs such as MYRADA. Especially, when there is little data, hydrological and water resources models can help improve the understanding of the physical system. Given there is prior knowledge of the monitoring variables NGOs use, and where their data is being sourced, simulated values can extend their records and may bring a dynamic and holistic vision to static isolated assessments.

It is recommended that phase 2 applies a dedicated web app with easy-to-read dashboards, displaying exactly what the project partners need. Noticeably from the technical workshop feedback, graphical and succinct tables/maps/figures, accompanied by a help functionality, could be configured to directly match their specific use cases. This would require heavy involvement and ownership by project partners, where the design of the use case stories to the qualitative/quantitative indicators are based on their data and calculations. Training in the use of this should be administered by members of their own organization after a session with the developers. Training may cover additional themes such as data management (collection, maintenance, storage), monitoring, modelling or GIS.

The indicators estimated during this assignment could be used operationally by FW’s partners to support the communities they work with. DHI’s approach demonstrated at the Taluk level in this pilot study, can be replicated to other areas in Karnataka and India. The water resources modelling concept lends itself to operational use due to the low execution time and the data streams required. In the future, it could be used for extreme event assessment such as drought and the testing of different strategies and policies.

Moreover, it has been shown that when official monitoring data from authorities is sparse, it is possible to use Earth Observation based data to fill some of the gaps. Due to the wealth of publicly and freely available by Indian and international sources, operationalization of the indicatos is effectively possible without financial dependencies.

Finally, the approach piloted resulted in a depiction of past conditions at the watershed level and the consistent impact of planned development in association with climate change. In the future, to support planning decisions, a measure of different sources of uncertainty should be added to the study, a requirement for robust decision-making where FW's partners and potentially extended stakeholder groups are provided with a way to conceptualize scenarios and results that carry probability and likelihood to inform their choices.

7 References

/1/ Apoorva R., V. Srinivasan, D.S. Kumar, 2021. Commercial, industrial & institutional water use in Bangalore. Environment and Development Discussion Paper No.4. Bengaluru: Ashoka Trust for Research in Ecology and the Environment.

/2/ Bangalore Metropolitan Region Development Authority (BMRDA), 2014. Master Plan for Anekal Local Planning Area 2031 – Zoning Regulations.

/3/ Bangalore Metropolitan Region Development Authority (BMRDA), 2017. Revised Master Plan for Bengaluru - 2031 (Draft): Volume 4 – Planning District Report.

/4/ BIS, 2012. Indian Standard for Drinking Water - Specification (2nd Revision) IS-10500: 2012. Bureau of Indian Standards, New Delhi. http://cgwb.gov.in/Documents/WQ-standards.pdf

/5/ Bonansea M, Rodriguez C and Pinotti L. 2018. Assessing the potential of integrating Landsat sensors for estimating chlorophyll-a concentration in a reservoir. Hydrology Research. Vol. 49(5), pp. 1608-1617.

/6/ CGWB, 2013, Ground Water Information Booklet, Bangalore Urban District, Karnataka, Central Groundwater Board, South western region, Bangalore, Ministry of water resources, Government of India, Mar-2013

/7/ CGWB, 2016. Dynamic Groundwater Resources of Karnataka, March – 2013, Groundwater Directorate, Minor Irrigation and Groundwater Development Department, Govt. of Karnataka & Central Groundwater Board, South Western Region, Bangalore,

/8/ CGWB, 2017. Dynamic Groundwater Resources of Karnataka, March – 2017 (broken link), Groundwater Directorate, Minor Irrigation and Groundwater Development Department, Govt. of Karnataka & Central Groundwater Board, South Western Region, Bangalore

/9/ CGWB a, 2021. Dynamic Groundwater Resources of Karnataka, March – 2020, Groundwater Directorate, Minor Irrigation and Groundwater Development Department, Govt. of Karnataka & Central Groundwater Board, South Western Region, Bangalore

/10/ CGWB b, 2021. Ground water yearbook 2020-21, Central Groundwater Board, South Western Region, Bangalore, Department of Water Resources, RD & GR, Ministry of Jal Shakti

/11/ Dekker AG, Zamurovi´c-Nenad Ž, Hoogenboom HJ and Peters SWM. 1996. Remote sensing, ecological water quality modelling and in situ measurements: A case study in shallow lakes. Hydrological Sciences Journal. Vol. 41, pp. 531-547.

/12/ FAO, https://www.fao.org/3/S2022E/s2022e07.htm accessed on 28 Feb 2023

/13/ Agriculture Department, State of Karnataka, URL: https://raitamitra.karnataka.gov.in/storage/pdf-files/Target2022-23.pdf accessed on 22 Feb 2023

/14/ CPHEEO, 1999. Manual on Water Supply and Treatment. 3rd edition-Revised and Updated. Central Public Health and Environmental Engineering Organization (CPHEEO), Ministry of Urban Development (MoUD), Govt. of India, New Delhi. https://www.indiawaterportal.org/sites/default/files/iwp2/manual_on_water_supply_and_treatment_cpheeo_moud_1999.pdf

/15/Department of Civil Engineering, IIT Hyderabad and Vassar Labs IT Solutions, 2020. User Manual for INDIA GEC Software (Automation of Estimation of Dynamic Ground Water Resources using GEC-2015 methodology and Related Research work to improve GEC Assessment).

/16/Government of Karnataka and Central Ground Water Board, 2021. Dynamic Ground water Resources of Karnataka, March - 2020.

/17/India-WRIS, 2012, River Basin Atlas of India, RRSC-West, NRSC, ISRO, Jodhpur, India.

/18/Indian Meteorological Department, URL: http://aws.imd.gov.in:8091/, Office of Climate Research & Services, Pune, India.

/19/Intergovernmental Panel on Climate Change, 2023. Synthesis Report of the IPCC Sixth Assessment Report (AR6), URL: https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf

/20/Keith D, Rover J, Green J, Zalewsky B, Charpentier M, Thursby G and Bishop J. 2018. Monitoring algal blooms in drinking water reservoirs using the Landsat-8 Operational Land Imager. International Journal of Remote Sensing. Vol. 39, pp. 2818-2846.

/21/Lehner, B., Grill G. (2013). Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. Hydrological Processes, 27(15): 2171–2186. https://doi.org/10.1002/hyp.9740

/22/Messager, M.L., Lehner, B., Grill, G., Nedeva, I., Schmitt, O. (2016). Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nature Communications, 7: 13603. https://doi.org/10.1038/ncomms13603

/23/Ministry of Water Resources, 2012. River Basin Atlas of India.

/24/Ministry of Water Resources, 2014. Watershed Atlas of India, Version 2.0.

/25/MSMEDI, 2016. District Industrial Profile, Bengaluru Urban, the Silicon Valley of India and Technology base in Asia. https://msmedibangalore.gov.in/files/Bengaluru%20Urban.pdf

/26/NRSC, 2019. Land Use / Land Cover database on 1:50,000 scale, Natural Resources Census Project, LUCMD, LRUMG, RSAA, National Remote Sensing Centre, ISRO, Hyderabad.

/27/O'Neill, B.C., E. Kriegler, K.L. Ebi, E. Kemp-Benedict, K. Riahi, D.S. Rothman, B.J. van Ruijven, D.P. van Vuuren, J. Birkmann, K. Kok, M. Levy, W. Solecki, 2015. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change, doi:10.1016/j.gloenvcha.2015.01.004.

/28/Riahi, K. et al., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Change 42, 153–168.

/29/Subba Rao N. 2018. Groundwater quality from a part of Prakasam district, Andhra Pradesh, India. Applied Water Science. Vol. 80, pp. 30.

Appendix A Stakeholder workshop

Appendix A.1 Attendance list

	Name	Organization	Role	Status	Contact	Invited
1	Sivashankar	Myrada	NGO Partner & Presenter	Confirmed	myradaksm@gmail.com	Yes - Hamish
2	Venkata Reddy	Myrada	NGO Partner	TBC		
3	Raghsvendra Rao Sudi	Myrada	NGO Partner	TBC		
4	Subrata Singh	Foundation for Ecological Security (FES India)	NGO Partner & Presenter	Confirmed	subrat@fes.org.in	Yes - Hamish
5	Himanshu Kulkarni	ACWADAM	Workshop Partner	Confirmed	admin@acwadam.org	Yes - Hamish
6	Shoury Reddy	Bala Vikasa	Hub Partner	Confirmed	madhu@balavikasa.org	Yes - Hamish
7	Madhu Sudan A	Bala Vikasa	Hub Partner	Confirmed	shoury@balavikasa.org	Yes - Hamish
8	Silvia Leirião	DHI Group	Technical Partner & Presenter	Confirmed	sls@dhigroup.com	Yes - Hamish
9	Vikrant Vijay Singh	DHI Group	Technical Partner	Confirmed	vvsi@dhigroup.com	Yes - Hamish
10	Tirumaleshwara Reddy	DHI Group	Technical Partner	Confirmed	trne@dhigroup.com	Yes - Hamish
11	Craig Dsouza	Centre for Social and Environmental Innovation, ATREE	Knowledge Partner	Confirmed	craig.dsouza@atree.org	Yes - Hamish

12	Senior Hydrologist, ATREEAnjali Neelakantan	Centre for Social and Environmental Innovation, ATREE	Knowledge Partner	Wants to listen in via online mode		Yes - Hamish	
13	Jon Shepherd	Frank Water	Project Team & Presenter	Online	jshepherd@frankwater.com	Yes - Hamish	Online
14	Praveena Sridhar	Frank Water	Project Team & Presenter	Confirmed	psridhar@frankwater.com	Yes - Hamish	
15	Hamish Hay	Frank Water	Project Team	Online	hhay@frankwater.com	Yes - Hamish	Online
16	Sachin Tiwari	Frank Water	Project Team	Confirmed	stiwari@frankwater.com	Yes - Hamish	
17	Shabir Hussain	WaterforPeople India	Observer		shussain@waterforpeople.org	Yes - Hamish	
17.1	Vinay Harswal	WaterforPeople India	Observer		vharswal@waterforpeople.org	Yes - Hamish	Online
18	Bishwadeep Ghose	Water for People India	Observer	JS	bghose@waterforpeople.org	Yes - Hamish	
19	Puneet Srivastava	WaterAid India	Observer	JS contact	PuneetSrivastava@wateraid.org	Yes - Hamish	
20	~~Kavita Tiwari~~	~~Water Aid India~~	~~Observer~~	~~JS contact~~	~~KavitaTiwari@wateraid.org~~		
21	Vincent Ca...	WaterAid UK	Observer	JS	VincentCasey@wateraid.org	Yes - Hamish	
22	Shiny Saha	IRC WASH India	Observer	JS	shiny@ircwash.org	Yes - Hamish	

23	Ruchika Shiva	IRC WASH India	Observer	JS	ruchika@ircwash.org	Yes - Hamish	
24	WOTR Contact			Praveena to check			
25	Philip Songa	Arup	Observer	Hamish/Jon to check?	philip.songa@arup.com	Yes - Hamish	
26	Freya Scott	Arup	Observer	Hamish/Jon to check?	Freya.Scott@arup.com	Yes - Hamish	
27	Annabella McNamara	Arup	Observer	Hamish/Jon to check?	Annabella.McNamara@arup.com	Yes - Hamish	
28	Puneet Srivastava	WaterAid	Observer	Praveena to check	PuneetSrivastava@wateraid.org	Yes - Hamish	
29	Pankaj Anand	Oxfam	Observer	Jon to check?	Pankaj@oxfamindia.org	Yes - Hamish	
30	Ashish Bharadwaj	AWS India	Observer	Write with an option to participate via online mode	ashish@a4ws.org	Yes - Hamish	Online
31	Maheen Malik	AWS Pakistan	Observer	Write with an option to participate via online mode	maheen@a4ws.org	Yes - Hamish	Online
32	Client	Client	Observer			Yes - Hamish	Online

Appendix A.2 Workshop Agenda

Time	Title	Responsible
09.00	**Welcome and introductions** Opening remarks by Frank Water stating the purpose of the workshop, specific objectives and intended outcomes for the day	Frank Water
09.15	**BtB portal and earth observation data app** Overview and understanding of available near real time data for water resources assessment • Hands-on exercises – based on the EO data app • Knowledge and understanding of available data and ability to view, analyse and download datasets • Feedback	DHI
10.15	**Break**	
10:30	**Use Case 1 – Civil Society Use Cases** Presentation of data needs for community capacity building and involvement in water management and planning • Overview of current situation • Monitoring/reporting data being used, methods and tools • Data gaps	Frank Water and/or NGO partner All

Time	Title	Responsible
	• Discussion	
11:30	**Use Case 2 – Agriculture and Industrial Use Cases** Presentation of knowledge to date of industrial water use • Water demand/use information flow • Internal monitoring/reporting data being used and known gaps • Discussion	Frank Water and/or NGO partner All
12.00	**Lunch**	
13.00	**Presentation of the modelling approach** • Methodology and technology applied • Preliminary results	DHI
13.30	**Groupwork** Assessment of preliminary results and how they can be used • Group discussions and feedback collection	DHI and Participants
14.30	Presentations of the Groupwork exercise and discussion	Participants
14.45	Break	
15.00	**Presentation of indicator framework and future scenarios** • Description of proposed indicator framework • Presentation of methodology for development of future scenarios	DHI
15.15	**Groupwork** Guided group discussions whereby participants discuss the scenarios, indicators and propose recommendations	DHI and Participants
15:45	Presentations of the findings and discussion	Participants
16.15	**Final remarks and closing** Reflections on the day - sharing of achievements, challenges and recommendations – and next steps.	Frank Water
16.30	**End**	

Appendix A.3 Workshop findings

Prior to presenting the conclusions with regards to the portal, it is noted that, for this assignment DHI's existing IT framework was to be used to facilitate result and EO-based data viewing and inspection. The portal was not intended to support decisions, nor provide dashboards for specific users.

Participants were mostly senior managers of FW's project partners, NGO's working with local communities in Anekal promoting sustainable water management amongst other areas of intervention (photograph in Figure 2.2).

Figure 2.2 Group photograph of the technical stakeholder workshop.

Starting with session 1, feedback from using the portal was generally positive, however, it was recorded that availability for following the step-by-step exercises during the 3 sessions was overall diminished. The only conclusion that may be drawn relates to the capacity of participants to use digital maps and online tools to analyse spatial/temporally distributed datasets. Key points for improvement recorded are the following:

- The dataset selection table is overwhelming for "non-technical" users
- It would be better to have dashboards with graphical model representations or pictorials of the water balance
- Suggestion to have information/tools that aid with interpretation of indicators

The above list of suggestions, which describe a new purpose for a BtB portal other than the one in this assignment, leads to the conclusion that there is a need to have decision support technology.

Session 2 resulted in prolific discussions, as participants made efforts to understand the water resources modelling approach, including the model calibration. There was concern regarding the applicability of some of the model inputs due to these coming from global data sources, and regarding the overall utility of a modelling approach versus a land use map alone. Consensus around the former was reached with recognition that the global datasets based on EO are widely used in India and all over the world to supplement ground-based measurements. The utility of applying a model was addressed in session 3 about modelling scenarios and indicators.

Lastly, in Session 3, a key conclusion is that climate change is not a priority for the participants in their water resources planning. However, participants became very interested and when looking at projected land use instead, and how a model can estimate water resources availability, water use and deficit. In addition, using the appropriate framework of indicators, it is possible to compare the current conditions and the projected conditions. A list of indicators was presented and discussed with the stakeholders. From the list, the indicators considered most important were water supply/deficit and watershed stress.

Finally, the following recommendations were made, which will be useful to FW for a next BtB phase:

- Have the indicators summarized by hydrological year and seasons
- Have indicators per capita (water supply)
- Indicators that show economic trade-offs
- Indicators related to social welfare, happiness, time spent collecting water, biomass
- Qualitative indicators on sustainability, governance and water use practices

Appendix B Field visit

A field visit took place on the 14th of February 2023 for the DHI team to visit some of the places in and around Anekal Taluk, the targets were pre-selected by FW, with the aim of:

- Improvement of the understanding of local conditions
- Understand FW's stakeholder MYRADA's work process in Malur block on soil and water conservation
- Understand urban sprawl into Anekal town from the Bengaluru city area
- Understanding local conditions of two lakes a) Dodda Kere and b) Haragade in Anekal taluk

The first stop was at Doddanalla village in Malur block of Kolar district, Karnataka, 20 km northeast of Anekal taluk administrative boundary. The team met MYRADA's representative Mr. Venkata Reddy who took the team to a percolation tank built by MYRADA in 2019 and demonstrated the administrative and technical process around having a percolation tank in a village. Each tank is supervised by Tank User Group (TUG) which include members from Gram Panchayat and MYRADA specialist(s). He also explained the purpose of the percolation tank, which is to augment groundwater recharge and promote sustainable use of groundwater. The team then visited another percolation tank located in 'Alagondahalli' village of Hosakote Takuk of Bangalore rural district, accompanied by MYRADA representative, see Figure 2.3.

Figure 2.3 Visit to a percolation tank for groundwater recharge to support agricultural water supply

The team stopped in the middle way between Anekal town and Anekal admin boundary to witness urban sprawl. Several agricultural land plots are converted to industrial/commercial holdings.

The Dodda kere and the Haragade lakes (Figure 2.4 and Figure 2.5) were visited along with Mr. Dharmendra, Field Survey Personnel from MYRADA to explore the options of inclusion in the baseline model as examples of surface water sources. Attempts to collect data were made and the result has been presented in the "Data collection and mapping report", namely, the apparent purposes for the lakes and approximate dimensions as well as observations on water quality.

Figure 2.4 Snapshots of google earth imagery of lakes Haragade to the left and Dodda kere to the right-hand side and their surrounding land use/cover

Figure 2.5 Photographs of field visit to the lake Dodda kere with visible impacts by severe eutrophication

Appendix C Technical reference

To maintain the final report at a easily consumable vehicle of information, we have created a technical reference containing the detailed description of some of the analysis conducted by the team, regarding land use/land cover and groundwater quality.

Appendix C.1 LULC analysis

The following sections describe the methodological steps leading to the post-classification change detection of the LULC grids for years 2010, 2022 and 2031.

Data processing

The data processing done for Anekal tehsil for 2010 and 2022 can be divided into two steps:

- Land Use Land Cover Classification
  - Acquisition of Landsat imageries and generation of seamless image mosaic for 2010 and 2022.
  - Geo-rectification using Global Positioning System's (GPC) and subsequent resampling the images into a common coordinate system and pixel size of 30 m.
  - Image subset creation for highlighting area of interest.
  - Land cover classification using both object-oriented classification and visual image interpretation.
- Change Detection and Conversion Matrix
  - Post classification method of image change detection was implemented:
  - Images of two vintages (2010 and 2022) were classified according to classification scheme suggested by NRSC (2012), which is given in Table 4.3. As we are using moderate resolution satellite imageries with 30 m for preparation of LULC data, and level 3 classification such as commercial, public and semi-public, public utilities and recreations cannot be identified on these satellite imagery through desktop study, we have decided to classified the satellite imageries for LULC within some limited classes as given in Table 4.3.
  - Detection of land use land cover changes between year 2010 and 2022 in the Anekal tehsil both in quantitative and qualitative terms using techniques of remote sensing (RS) and geographic information system (GIS).
  - Conversion matrix was created to better understand the changes in land use land cover in terms of direction of change (which land use encroached on which).

Land use land cover classification

To understand the physical change in Anekal tehsil, the land use and land cover (LULC) classification scheme developed by NRSC (2012)[3] was used with minor modification, and classification was performed using moderate resolution satellite imageries. There are two methods to classify the satellite imageries, (i) digital classification (supervised / unsupervised)[4] and (ii) manual classification (visual image interpretation). The first method

[3] NRSC. 2012. Manual of national land use / land cover mapping (second cycle) using multi-temporal satellite data. Department of Space, Hyderabad. https://bhuvan-app1.nrsc.gov.in/2dresources/thematic/2LULC/lulc1112.pdf

[4] Supervised is mainly a human-guided classification. In contrast, unsupervised classification is calculated by the software. Supervised classification is based on the idea that a user can select sample pixels in an image that are representative of

applies clustering algorithms using spectral, textural, or contextual measures to perform classification with some (supervised) or no (unsupervised) human intervention. Visual interpretation needs human interpretation to identify and classify the image into objects.

Algorithm based classification is suitable with low to medium resolution images, where identification of real-world objects is not very clear. However, with an increase in spatial resolution, the image is more revealing and inter-object spectral noise makes it difficult to successfully extract information in an efficient manner. Visual interpretation is far superior in terms of extraction of information, but it is very slow. In such scenario, it was decided to use both methods for land use and land cover classification.

Digital classification (unsupervised) method has been used for extraction of (i) agricultural crop land, (ii) agricultural fallow land, (iii) vegetation, (iv) scrub - barren land, (v) forest area, (vi) water bodies, and (vii) river-drain, while the traditional visual image interpretation method has been used for digitization of other land use categories, (viii) built-up area (urban), (ix) built-up area (rural), (x) industrial area, and (xi) mining. As historical high-resolution satellite imageries (GeoEye, WorldView, QuickBird)[5] is also available on GoogleEarth, then these land use / land cover data layers have been verified through best available (same time period of year 2010 and 2022) GoogleEarth satellite imagery. Land use and land cover statistics were generated for the 2010 and 2022, and maps of Anekal tehsil for 2010 and 2022 are presented in Figure 4.1.

Land use land cover change detection

Multi-temporal satellite images can be used to record changes in land use land cover (Aspinal et al., 2008)[6]. Change detection methods have been divided into either pre-classification (Lillesand et al., 1989[7]; Liu et al., 2015[8]), where changes in the reflectance classes are measured or post-classifications where changes in the information classes are measured (Howarth et al.,1981)[9].

The advantage of post-classification change detection is the representation of change in terms of information classes, which are more relevant than the digital numbers on an image. However, this method is dependent on the classification accuracies.

To measure changes in the Anekal tehsil between 2010 and 2022, post-classification change detection was applied. The change detection statistics were used to create a land use land cover conversion matrix. A conversion matrix displays changes in each land use land cover class and gives information regarding direction of change.

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specific classes and then direct the image processing software to use these training sites as references for the classification of all other pixels in the image. Unsupervised classification is where the outcomes (groupings of pixels with common characteristics) are based on the software analysis of an image without the user providing sample classes.

[5] These are the very high-resolution satellite (VHRS) images with <50 cm spatial resolution owned by DigitalGlobe, USA (United States of America).

[6] Aspinal RJ and Hill MJ. 2008. Land use change - science, policy, and management. Boca Raton: CRC Press.

[7] Lillesand TM and Kiefer RW. 1994. Remote sensing and image interpretation (4th ed.). New York, Wiley.

[8] Liu T and Yang X. 2015. Monitoring land changes in an urban area using satellite imagery, GIS, and landscape metrics. Applied Geography. Vol. 56, pp. 42-54.

[9] Howarth PJ and Wickware GM. 1981. Procedures for change detection using Landsat digital data. International Journal of Remote Sensing. Vol. 2(3), pp. 277-291.

Appendix C.2 Groundwater quality analysis

It has been chosen to include in the investigation, the data measured at 9 boreholes outside the study area, to be able to generate appropriate values via interpolation at the study area boundary.

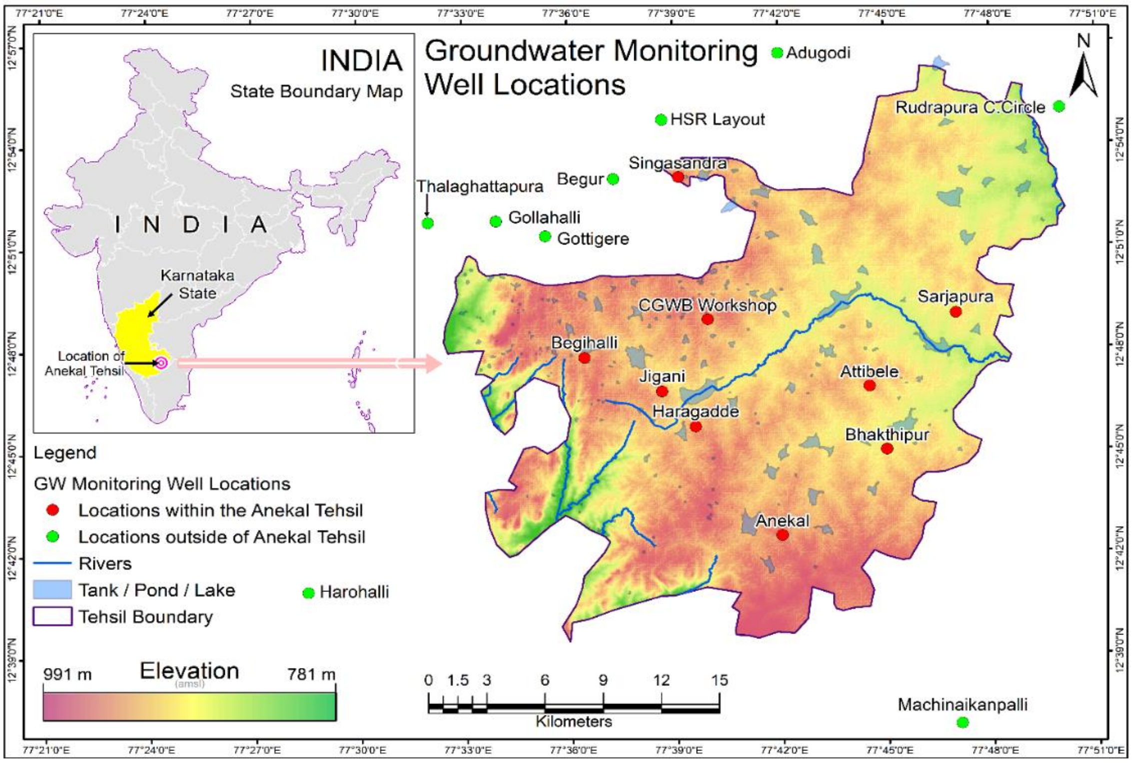

Figure C.2.1 Groundwater quality monitoring well locations in and around Anekal Tehsil

Table A lists the standard water quality parameters for the 16 physicochemical parameters used in this study.

Table C.2.1 Acceptable limit of various water parameters, and summary of the physical and chemical parameters with statistical analysis

S. No.	Water Quality Parameters	Indian Standards (IS 10500: 2012)[10]		WHO (2017)[11]	Data Range (Average 2010-2021)			Skewness	Kurtosis
		Desirable Limit	Permissible Limit		Min.	Max.	Ave.		
1	pH (Power of Hydrogen)	6.5 to 8.5	No relaxation	6.5-8.5	7.30	10.18	8.20	1.42	1.50
2	Electrical Conductivity (EC) µS/cm	-	-	400-2000	335.00	2520.00	1164.00	0.52	-0.28
3	Total Hardness ($CaCO_3$) mg/L	300	600	-	50.00	680.00	336.00	0.21	-0.59
4	Total Alkalinity (TA) mEq/L	200	600	-	0.00	250.00	127.46	-0.43	-1.75
5	Calcium (Ca) mg/L	75	200	100-200	8.00	140.00	65.40	0.36	-0.90
6	Magnesium (Mg) mg/L	30	100	30-50	7.29	92.54	41.77	0.44	0.83
7	Sodium (Na) mg/L	-	-	20-1756	20.20	414.00	126.81	1.80	3.08
8	Potassium (K) mg/L	-	-	10-12	0.50	182.00	19.55	3.13	9.40
9	Carbonate (CO3) mg/L				0.00	60.00	5.16	3.38	12.18
10	Bicarbonate (HCO3) mg/L	200	600	-	91.53	723.00	241.38	1.85	4.33
11	Chloride (Cl) mg/L	250	1000	200-300	35.45	530.00	191.91	0.83	0.60
12	Sulfate (SO_4) mg/L	200	400	25-250	8.00	316.80	86.65	1.56	2.26
13	Nitrate (NO_3) mg/L	45	100	50	0.00	151.20	36.75	1.40	1.03
14	Fluoride (F) mg/L	1	1.5	0.6-4	0.16	2.76	0.63	3.00	11.21
15	Sodium Adsorption Ratio (SAR)				0.00	3.90	0.43	2.69	7.65
16	Residual Sodium Carbonate (RSC) mEq/L				0.00	0.00	0.00	0.00	0.00

[10] BIS. 2012. Indian Standard for Drinking Water - Specification (2nd Revision) IS-10500: 2012. Bureau of Indian Standards, New Delhi. http://cgwb.gov.in/Documents/WQ-standards.pdf

[11] WHO. 2017. Guidelines for drinking-water quality. 4th edition, incorporating the 1st addendum. Public Health and the Environment, World Health Organization (WHO), Geneva. https://www.who.int/publications/i/item/9789241549950

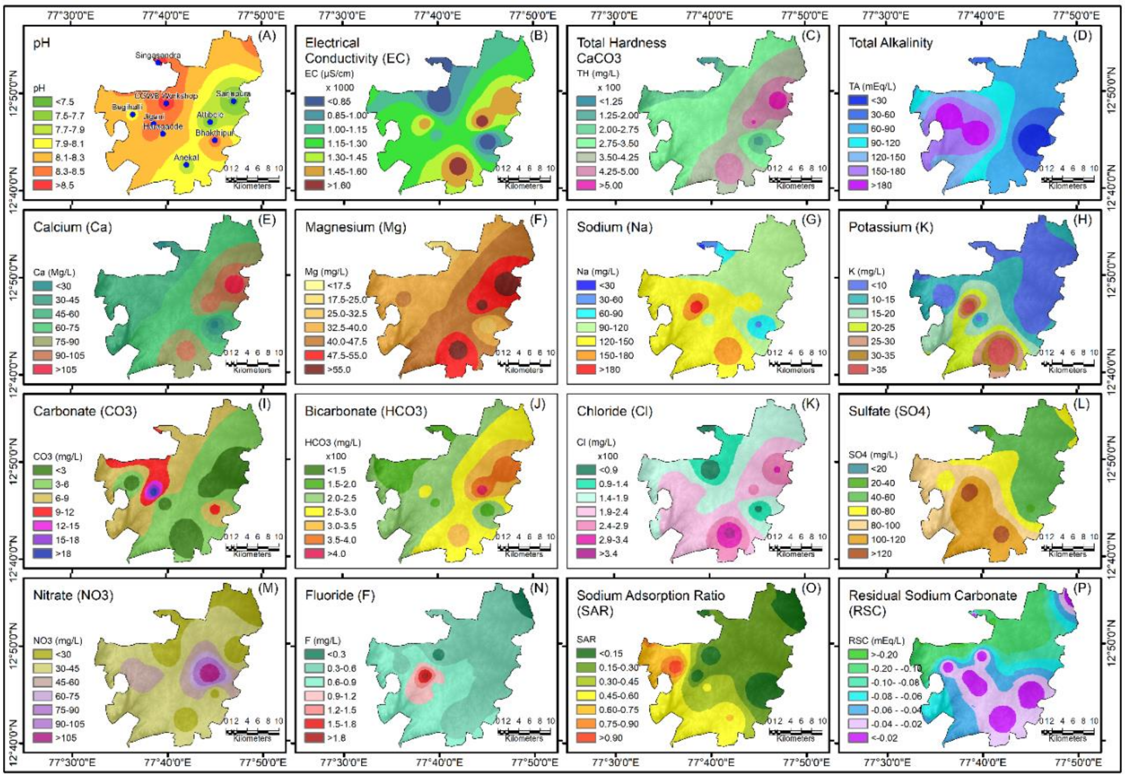

Figure C.2.2 Groundwater quality maps for 16 WQ parameters, based on average data (2010-2021)

Weighted arithmetic water quality index method (WAWQI)

This sub section details the calculation procedure to arrive at the GQI results. Using the most frequently measured water quality variables, the weighted arithmetic water quality index method classified the water quality according to the level of purity. The method has been widely employed by several scientists (Chowdhury et al., 2012)[12], and the calculation of WQI was made by Brown et al., 1972[13] by using the following equation:

WQI = Σ (Qi * Wi) / Σ Wi ………………………………………..……………………………… (1)

The quality rating scale (Qi) for each parameter is calculated by using this expression:

Qi = 100 * [(Vo - Vi) / (Sn - Vi)] ……………………………………………………….………. (2)

Where:
Vo = Observed value or actual value of individual parameter
Vi = Ideal Value of individual WQ parameter, it should be 0 for all WQ parameters except for pH =7.0 and DO = 14.6 mg/l
Sn = Standard permissible value according to national and international standard drinking water specification recommended by BIS, WHO, EU, EPA, ICME, CCME, ADWG, CPHEED, etc.
The unit weight (Wi) for each water quality parameter is calculated by using the following formula:

Wi = K / Sn ……………………………….……………...…………………………………. (3)

Where:

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[12] Chowdhury RM, Muntasir SY and Hossain MM. 2012. Water quality index of water bodies along Faridpur-Barisal Road in Bangladesh. Global Journal of Engineering and Technology. Vol. 2(3), pp. 1-8.

[13] Brown RM, McCleiland NJ, Deiniger RA and O'Connor MFA. 1972. Water quality index - crossing the physical barrier. Proceedings in International Conference on water pollution Research Jerusalem. Vol. 6, pp. 787-797.

K = Proportionality constant and can also be calculated by using the following equation:

$K = 1 / [(\Sigma 1/S1) + (\Sigma 1/S2) + (\Sigma 1/S3) + (\Sigma 1/S4) + \cdots\cdots\cdots + (\Sigma 1/S\infty)]$ …………………… (4)

Where:
S1, S2, S3, …….. are the actual value of individual parameter of water sample or sites.

Calculation of groundwater quality index (GWQI)

The weighted arithmetic water quality index (WAWQI) method has been used to calculate the water quality index (WQI) of Anekal tehsil. Available groundwater data from 2010 to 2021 have been used for generating of average data range for all groundwater monitoring locations. Since there is significantly data missing for all groundwater monitoring well locations and the various water quality parameters in year 2010 and 2021, the average data has been used. The data of years 2010, and 2021 has been used to generate the groundwater quality index (GWQI) and compare groundwater quality with respective year.

Groundwater quality data was considered as observed value (Vo), and according to WAWQI methods, all factors such as ideal value (Vi), standard permissible value (Sn), proportionality constant (K), unit weight (Wi), quality rating scale (Qi), and water quality index (WQI) have been calculated for both years 2010 and 2021 and presented in Table 7.1 and Table 7.2.

Table 7.1 Groundwater quality index calculation by WAWQI method for year 2010

Site Name	Vo (Observed Value)													
	pH	EC	TH	Alkalinity	CA	MG	NA	K	CO3	BiCab	CL	SUL	NIT	FLU
Anekal	7.85	1718.50	487.25	70.08	97.25	59.23	172.13	47.58	5.16	321.48	357.88	126.25	20.13	0.35
Attibele	7.56	1730.00	505.00	127.46	105.00	58.00	133.00	6.20	5.16	424.00	255.00	40.00	151.20	0.63
Begihalli	7.70	920.00	330.00	164.75	60.00	43.00	55.00	6.20	5.16	201.00	156.00	18.00	59.00	0.46
Bhakthipur	8.39	629.50	170.00	127.46	25.00	26.07	56.00	7.00	10.00	162.58	79.23	37.20	23.80	0.49
CGWB Workshop	8.60	550.00	336.00	127.46	65.40	41.77	126.81	19.55	5.16	241.38	35.50	86.65	7.66	0.16
Haragadde	8.29	1084.75	350.00	209.84	71.33	41.90	105.33	8.03	5.16	189.18	167.93	112.93	36.50	0.83
Jigani	8.45	1595.00	277.00	127.46	55.00	33.43	205.00	44.67	20.00	271.08	231.41	140.27	60.47	1.98
Sarjapura	7.46	1600.00	530.00	127.46	113.00	60.00	108.00	5.70	5.16	381.00	294.00	51.00	16.80	0.63
Singasandra	8.69	450.67	125.00	127.46	22.00	17.00	25.05	1.45	9.00	146.42	37.85	9.50	3.64	0.42

K =	0.90	99.54	30.98	13.85	5.61	4.02	8.28	0.65	0.70	25.53	10.64	3.73	1.60	0.05	
Sn =	8.50	2000.00	600.00	600.00	200.00	100.00	1756.00	10.00	60.00	600.00	1000.00	400.00	100.00	1.50	
(∑ Wi = 0.4906) Wi =	0.11	0.05	0.05	0.02	0.03	0.04	0.00	0.06	0.01	0.04	0.01	0.01	0.02	0.03	0.4906
Vi =	7	0	0	0	0	0	0	0	0	0	0	0	0	0	

Site Name	Quality Rating Scale (Qi) = 100 x (Vo-Vi) / (Sn-Vi)													
	pH	EC	TH	Alkalinity	CA	MG	NA	K	Fe	BiCab	CL	SUL	NIT	FLU
Anekal	56.50	85.93	81.21	11.68	48.63	59.23	9.80	475.75	8.60	53.58	35.79	31.56	20.13	23.33
Attibele	37.33	86.50	84.17	21.24	52.50	58.00	7.57	62.00	8.60	70.67	25.50	10.00	151.20	42.18
Begihalli	46.67	46.00	55.00	27.46	30.00	43.00	3.13	62.00	8.60	33.50	15.60	4.50	59.00	30.67
Bhakthipur	92.67	31.48	28.33	21.24	12.50	26.07	3.19	70.00	16.67	27.10	7.92	9.30	23.80	32.50
CGWB Workshop	106.67	27.50	56.00	21.24	32.70	41.77	7.22	195.50	8.60	40.23	3.55	21.66	7.66	10.96
Haragadde	86.00	54.24	58.33	34.97	35.67	41.90	6.00	80.33	8.60	31.53	16.79	28.23	36.50	55.50
Jigani	96.44	79.75	46.17	21.24	27.50	33.43	11.67	446.67	33.33	45.18	23.14	35.07	60.47	132.00
Sarjapura	30.67	80.00	88.33	21.24	56.50	60.00	6.15	57.00	8.60	63.50	29.40	12.75	16.80	42.18
Singasandra	112.73	22.53	20.83	21.24	11.00	17.00	1.43	14.50	15.00	24.40	3.79	2.38	3.64	27.98

Site Name	Qi * Wi														Final Calculation	
	pH	EC	TH	Alkalinity	CA	MG	NA	K	Fe	BiCab	CL	SUL	NIT	FLU	∑ Qi * Wi	WQI
Anekal	5.97	4.28	4.19	0.27	1.36	2.38	0.05	30.70	0.10	2.28	0.38	0.29	0.32	0.76	53.34	108.74
Attibele	3.95	4.31	4.35	0.49	1.47	2.33	0.04	4.00	0.10	3.01	0.27	0.09	2.42	1.38	28.20	57.48
Begihalli	4.93	2.29	2.84	0.63	0.84	1.73	0.01	4.00	0.10	1.43	0.17	0.04	0.95	1.00	20.96	42.73
Bhakthipur	9.79	1.57	1.46	0.49	0.35	1.05	0.02	4.52	0.20	1.15	0.08	0.09	0.38	1.06	22.21	45.27
CGWB Workshop	11.27	1.37	2.89	0.49	0.92	1.68	0.03	12.62	0.10	1.71	0.04	0.20	0.12	0.36	33.80	68.91
Haragadde	9.09	2.70	3.01	0.81	1.00	1.68	0.03	5.18	0.10	1.34	0.18	0.26	0.58	1.81	27.79	56.64
Jigani	10.19	3.97	2.38	0.49	0.77	1.34	0.06	28.83	0.39	1.92	0.25	0.33	0.97	4.31	56.20	114.56
Sarjapura	3.24	3.98	4.56	0.49	1.58	2.41	0.03	3.68	0.10	2.70	0.31	0.12	0.27	1.38	24.86	50.67
Singasandra	11.91	1.12	1.08	0.49	0.31	0.68	0.01	0.94	0.18	1.04	0.04	0.02	0.06	0.91	18.78	38.29

Table 7.2 Groundwater quality index calculation by WAWQI method for year 2021

Site Name	Vo (Observed Value)													
	pH	EC	TH	Alkalinity	CA	MG	NA	K	CO3	BiCab	CL	SUL	NIT	FLU
Anekal	7.87	1090.00	369.00	70.08	81.00	40.00	60.00	2.80	5.16	276.00	163.00	59.00	20.20	0.35
Attibele	7.56	1730.00	505.00	127.46	105.00	58.00	133.00	6.20	5.16	424.00	255.00	40.00	151.20	0.63
Begihalli	8.04	1280.00	316.25	207.38	57.00	42.07	128.38	3.45	5.16	184.48	228.18	71.00	50.42	0.47
Bhakthipur	8.39	629.50	170.00	127.46	25.00	26.07	56.00	7.00	10.00	162.58	79.23	37.20	23.80	0.49
CGWB Workshop	8.60	550.00	336.00	127.46	65.40	41.77	126.81	19.55	5.16	241.38	35.50	86.65	7.66	0.16
Haragadde	8.29	1084.75	350.00	209.84	71.33	41.90	105.33	8.03	5.16	189.18	167.93	112.93	36.50	0.83
Jigani	7.30	1525.00	571.00	127.46	113.00	69.00	71.00	8.10	20.00	399.00	223.00	37.00	125.40	1.98
Sarjapura	7.46	1600.00	530.00	127.46	113.00	60.00	108.00	5.70	5.16	381.00	294.00	51.00	16.80	0.63
Singasandra	7.46	1600.00	530.00	127.46	113.00	60.00	108.00	5.70	9.00	381.00	294.00	51.00	16.80	0.42

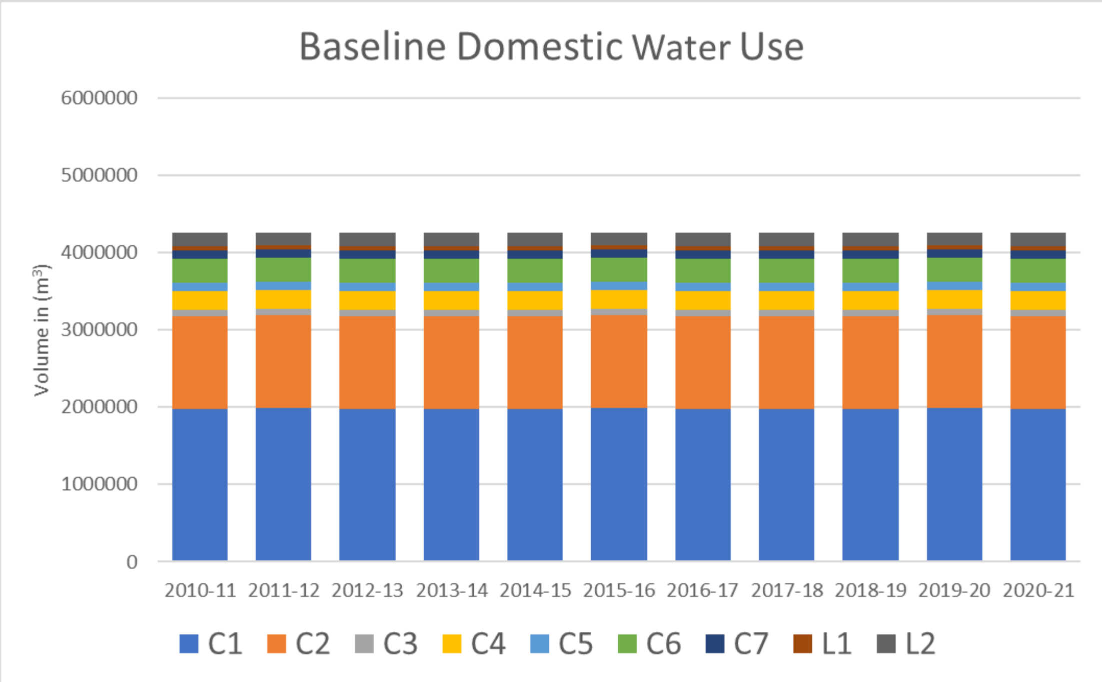
K =	0.87	117.49	39.85	14.10	7.39	5.00	10.02	0.62	0.70	28.79	13.80	5.90	2.48	0.05	
Sn =	8.50	2000.00	600.00	600.00	200.00	100.00	1756.00	10.00	60.00	600.00	1000.00	400.00	100.00	1.50	
(∑ Wi = 0.5523) Wi =	0.10	0.06	0.07	0.02	0.04	0.05	0.01	0.06	0.01	0.05	0.01	0.01	0.02	0.03	0.5523
Vi =	7	0	0	0	0	0	0	0	0	0	0	0	0	0	

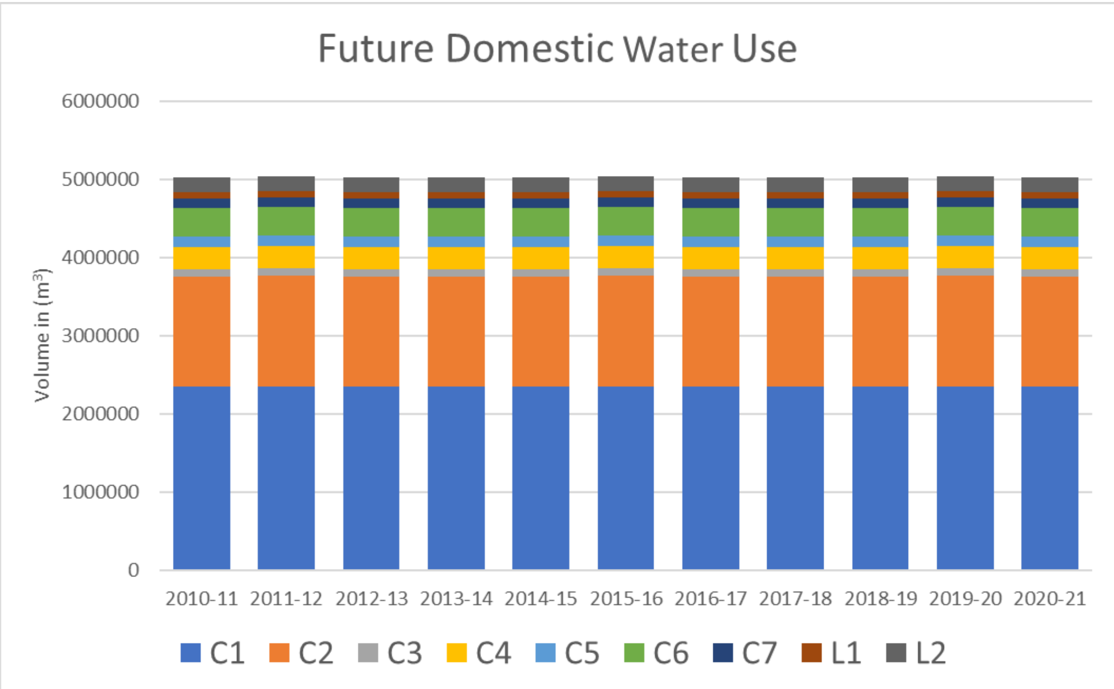
Site Name	Quality Rating Scale (Qi) = 100 x (Vo-Vi) / (Sn-Vi)													
	pH	EC	TH	Alkalinity	CA	MG	NA	K	Fe	BiCab	CL	SUL	NIT	FLU
Anekal	58.00	54.50	61.50	11.68	40.50	40.00	3.42	28.00	8.60	46.00	16.30	14.75	20.20	23.33
Attibele	37.33	86.50	84.17	21.24	52.50	58.00	7.57	62.00	8.60	70.67	25.50	10.00	151.20	42.18
Begihalli	69.33	64.00	52.71	34.56	28.50	42.07	7.31	34.50	8.60	30.75	22.82	17.75	50.42	31.56
Bhakthipur	92.67	31.48	28.33	21.24	12.50	26.07	3.19	70.00	16.67	27.10	7.92	9.30	23.80	32.50
CGWB Workshop	106.67	27.50	56.00	21.24	32.70	41.77	7.22	195.50	8.60	40.23	3.55	21.66	7.66	10.96
Haragadde	86.00	54.24	58.33	34.97	35.67	41.90	6.00	80.33	8.60	31.53	16.79	28.23	36.50	55.50
Jigani	20.00	76.25	95.17	21.24	56.50	69.00	4.04	81.00	33.33	66.50	22.30	9.25	125.40	132.00
Sarjapura	30.67	80.00	88.33	21.24	56.50	60.00	6.15	57.00	8.60	63.50	29.40	12.75	16.80	42.18
Singasandra	30.67	80.00	88.33	21.24	56.50	60.00	6.15	57.00	15.00	63.50	29.40	12.75	16.80	27.98

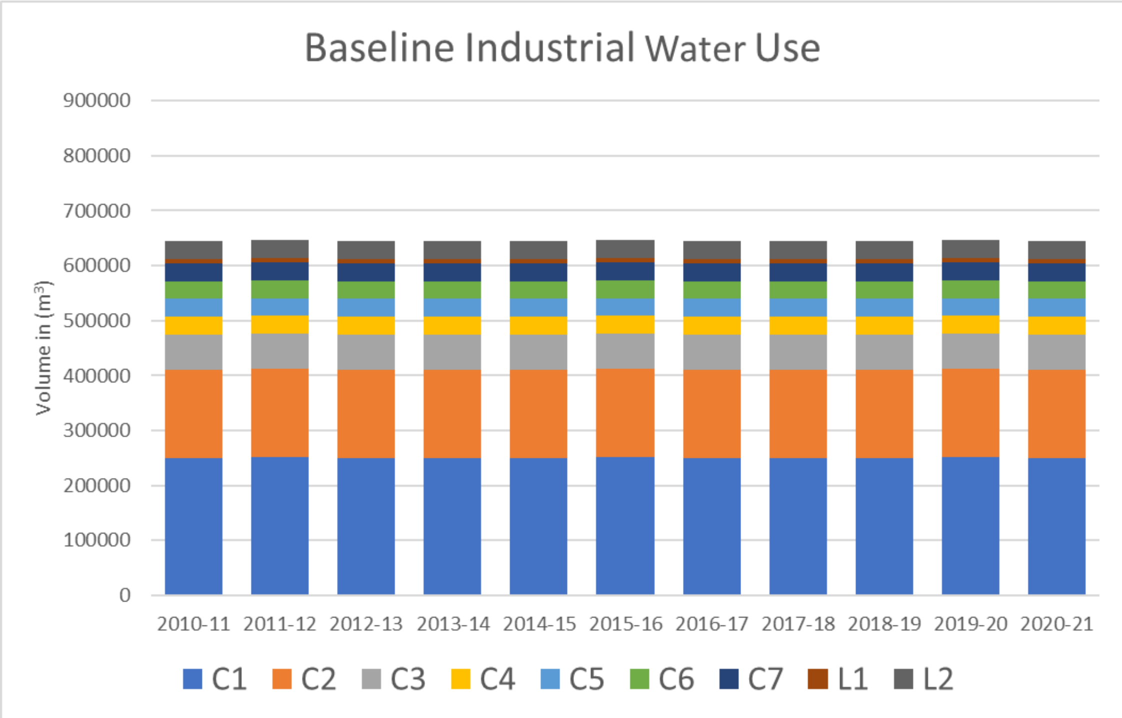
Site Name	Qi * Wi														Final Calculation	
	pH	EC	TH	Alkalinity	CA	MG	NA	K	Fe	BiCab	CL	SUL	NIT	FLU	∑ Qi * Wi	WQI
Anekal	5.96	3.20	4.08	0.27	1.50	2.00	0.02	1.75	0.10	2.21	0.22	0.22	0.50	0.76	22.80	41.28
Attibele	3.84	5.08	5.59	0.50	1.94	2.90	0.04	3.87	0.10	3.39	0.35	0.15	3.75	1.38	32.89	59.54
Begihalli	7.12	3.76	3.50	0.81	1.05	2.10	0.04	2.15	0.10	1.48	0.31	0.26	1.25	1.03	24.99	45.24
Bhakthipur	9.52	1.85	1.88	0.50	0.46	1.30	0.02	4.37	0.20	1.30	0.11	0.14	0.59	1.06	23.30	42.19
CGWB Workshop	10.96	1.62	3.72	0.50	1.21	2.09	0.04	12.21	0.10	1.93	0.05	0.32	0.19	0.36	35.29	63.89
Haragadde	8.84	3.19	3.87	0.82	1.32	2.10	0.03	5.02	0.10	1.51	0.23	0.42	0.91	1.82	30.17	54.62
Jigani	2.06	4.48	6.32	0.50	2.09	3.45	0.02	5.06	0.39	3.19	0.31	0.14	3.11	4.32	35.44	64.16
Sarjapura	3.15	4.70	5.87	0.50	2.09	3.00	0.04	3.56	0.10	3.05	0.41	0.19	0.42	1.38	28.44	51.49
Singasandra	3.15	4.70	5.87	0.50	2.09	3.00	0.04	3.56	0.18	3.05	0.41	0.19	0.42	0.92	28.05	50.78

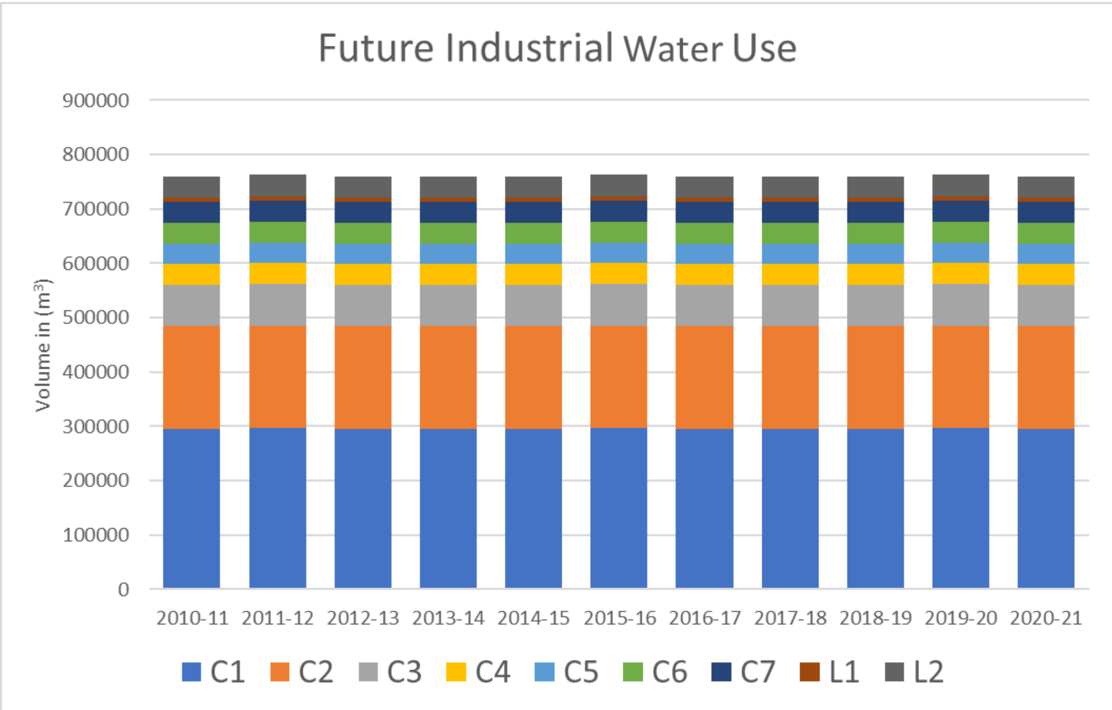
Appendix D Indicator plots for each watershed

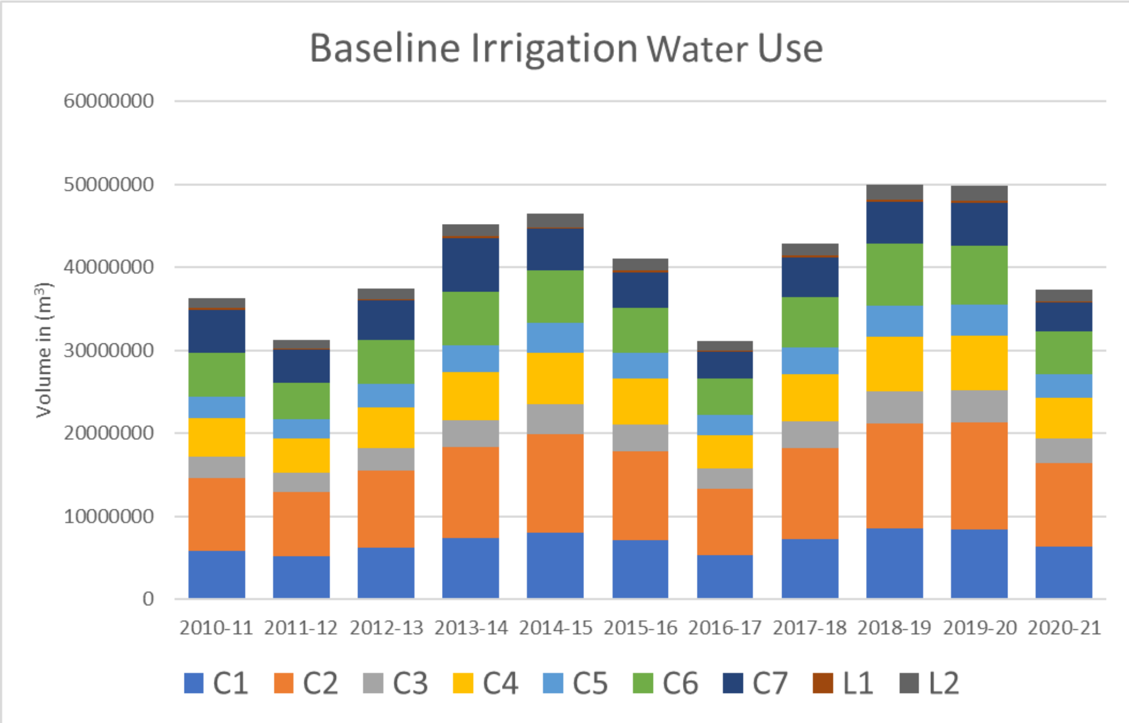
Appendix D.1 Current Water Use disaggregated by User

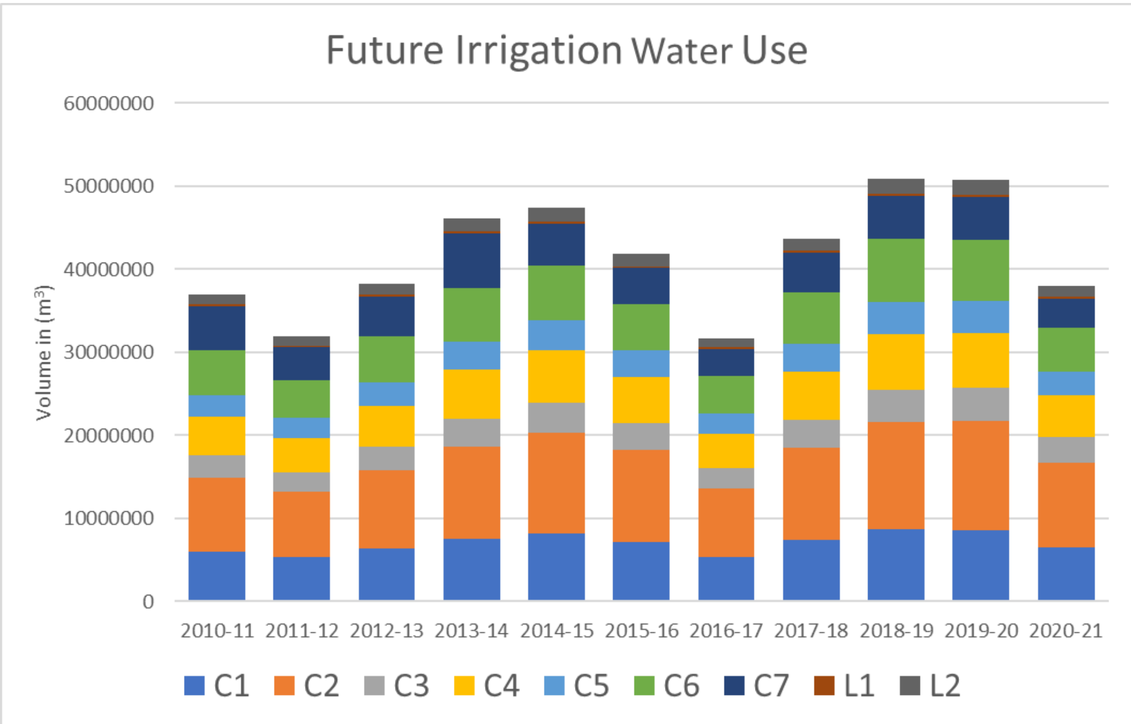




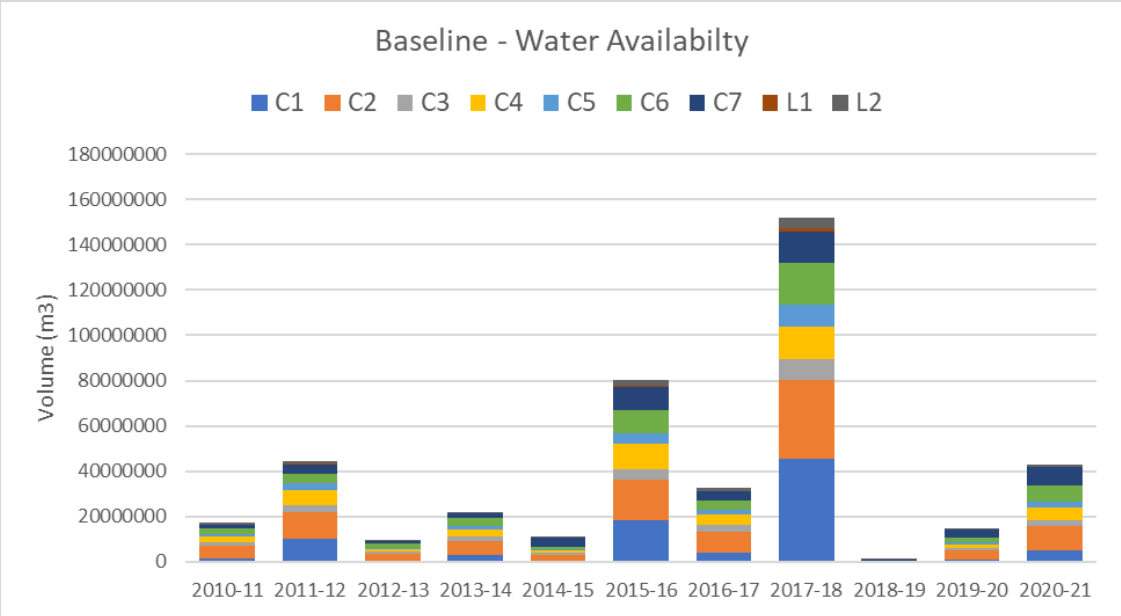

Baseline Industrial Water Use
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
Volume in (m³)
2010-11 2011-12 2012-13 2013-14 2014-15 2015-16 2016-17 2017-18 2018-19 2019-20 2020-21
C1 C2 C3 C4 C5 C6 C7 L1 L2

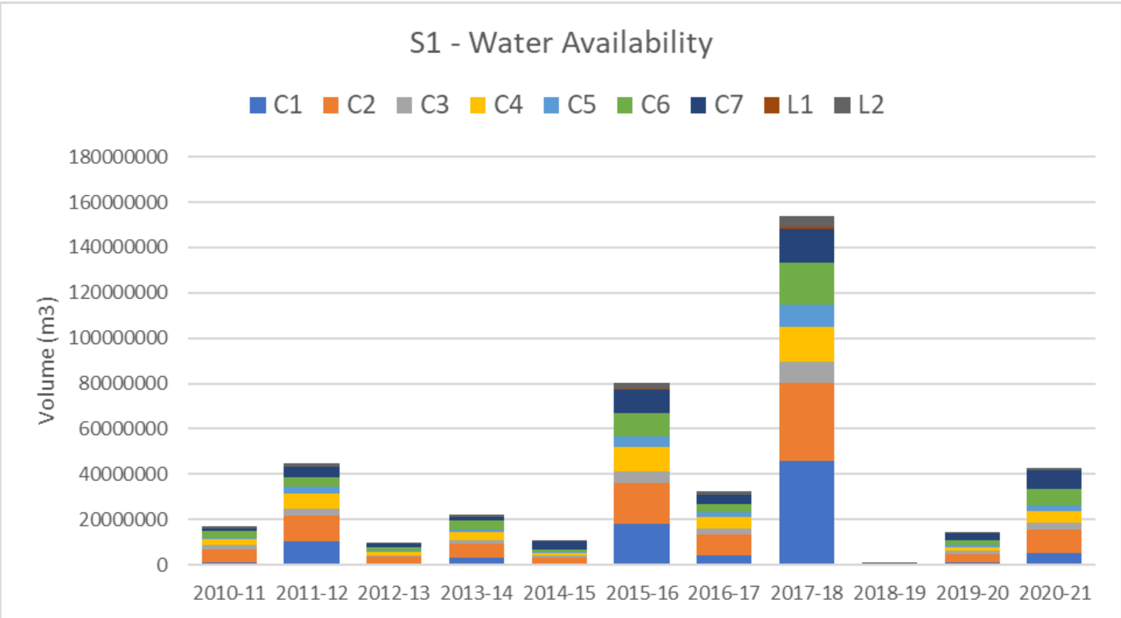

Future Industrial Water Use
900000
800000
700000
600000
500000
400000
300000
200000
100000
0
Volume in (m³)
2010-11 2011-12 2012-13 2013-14 2014-15 2015-16 2016-17 2017-18 2018-19 2019-20 2020-21
C1 C2 C3 C4 C5 C6 C7 L1 L2

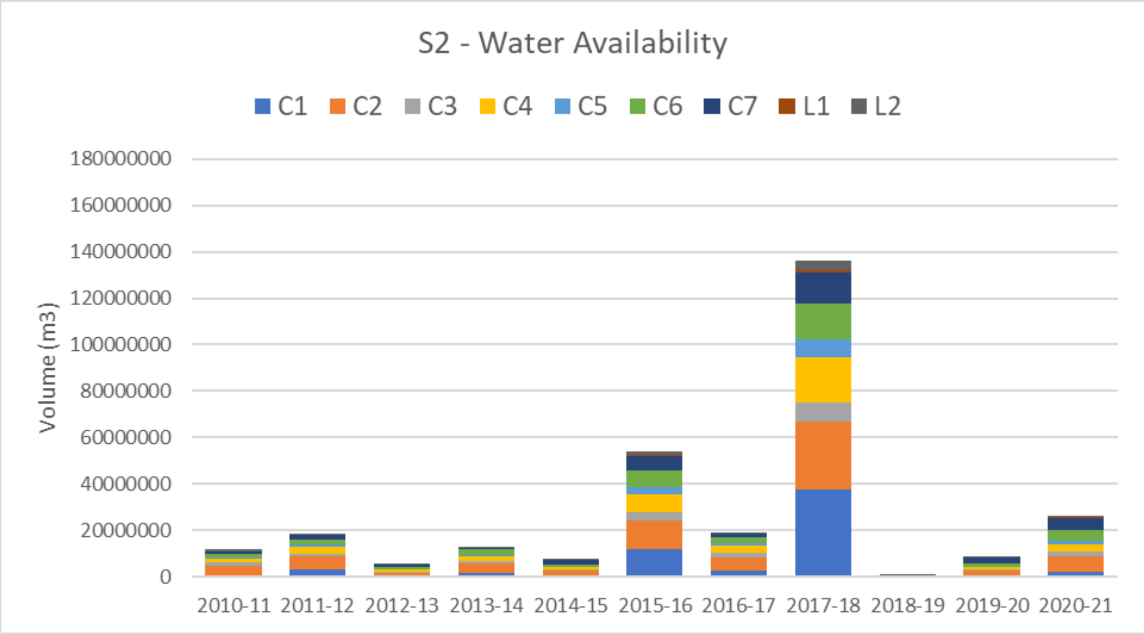

Baseline Irrigation Water Use
60000000
50000000
40000000
30000000
20000000
10000000
0
Volume in (m³)
2010-11 2011-12 2012-13 2013-14 2014-15 2015-16 2016-17 2017-18 2018-19 2019-20 2020-21
C1 C2 C3 C4 C5 C6 C7 L1 L2

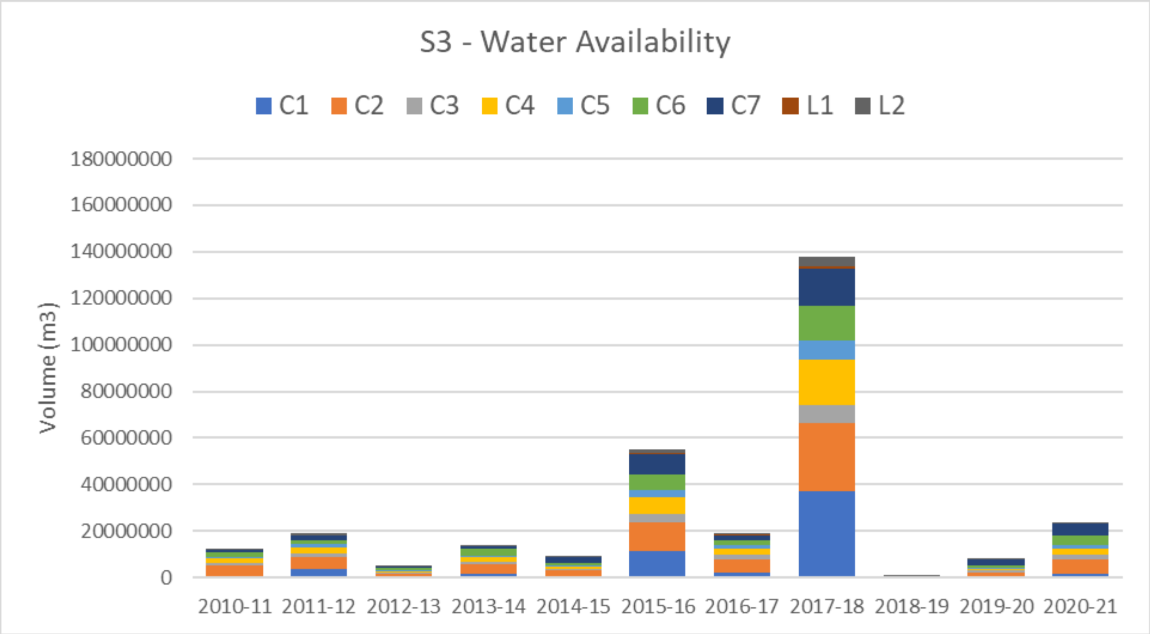

Future Irrigation Water Use
60000000
50000000
40000000
30000000
20000000
10000000
0
Volume in (m³)
2010-11 2011-12 2012-13 2013-14 2014-15 2015-16 2016-17 2017-18 2018-19 2019-20 2020-21
C1 C2 C3 C4 C5 C6 C7 L1 L2

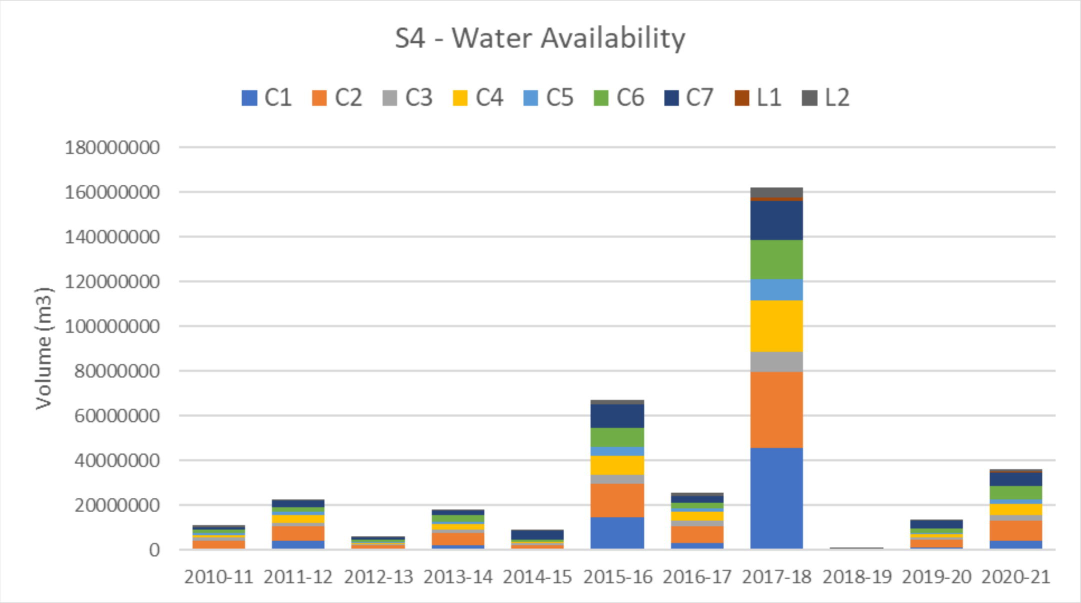
Appendix D.2 Current and projected total amount of water available for use



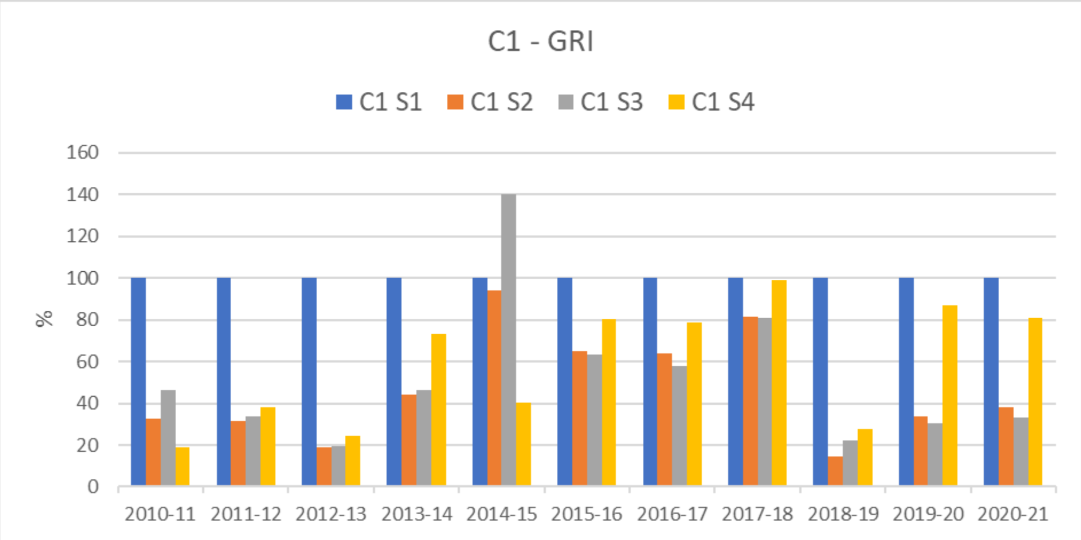


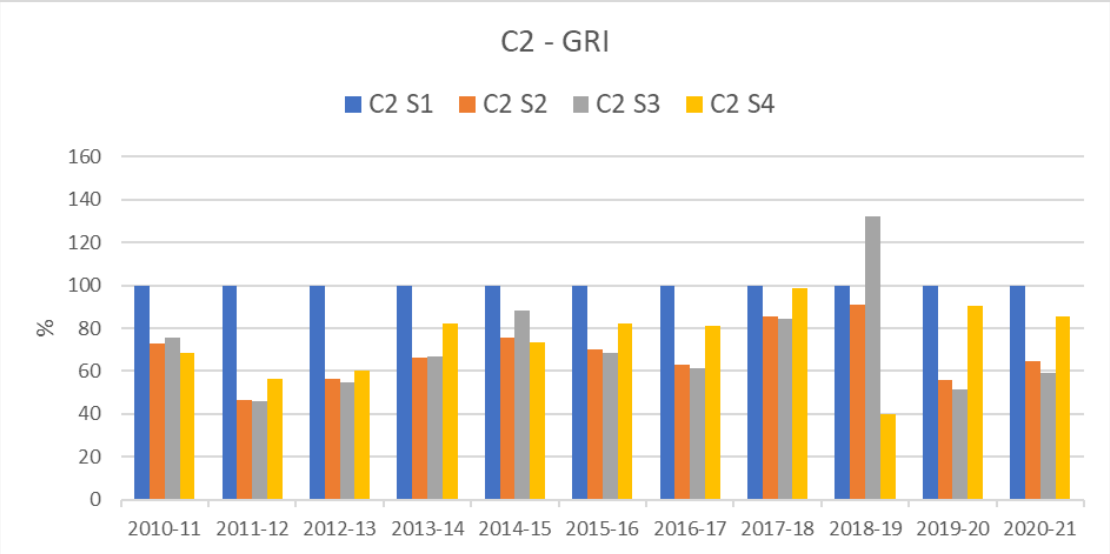

S2 - Water Availability
C1 C2 C3 C4 C5 C6 C7 L1 L2
Volume (m3)
180000000
160000000
140000000
120000000
100000000
80000000
60000000
40000000
20000000
0
2010-11 2011-12 2012-13 2013-14 2014-15 2015-16 2016-17 2017-18 2018-19 2019-20 2020-21

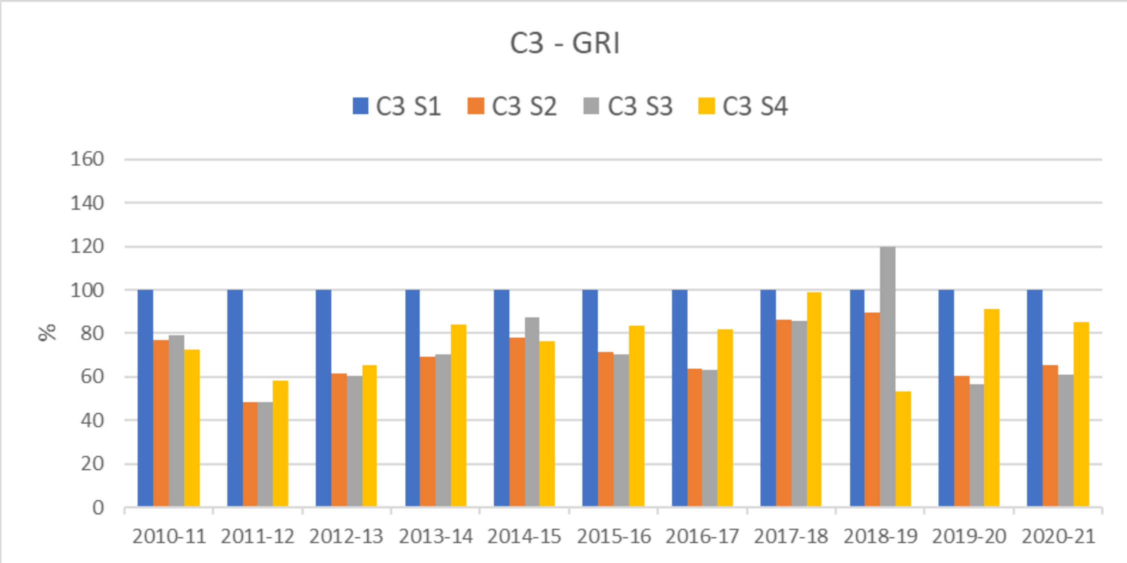

S3 - Water Availability
C1 C2 C3 C4 C5 C6 C7 L1 L2
Volume (m3)
180000000
160000000
140000000
120000000
100000000
80000000
60000000
40000000
20000000
0
2010-11 2011-12 2012-13 2013-14 2014-15 2015-16 2016-17 2017-18 2018-19 2019-20 2020-21

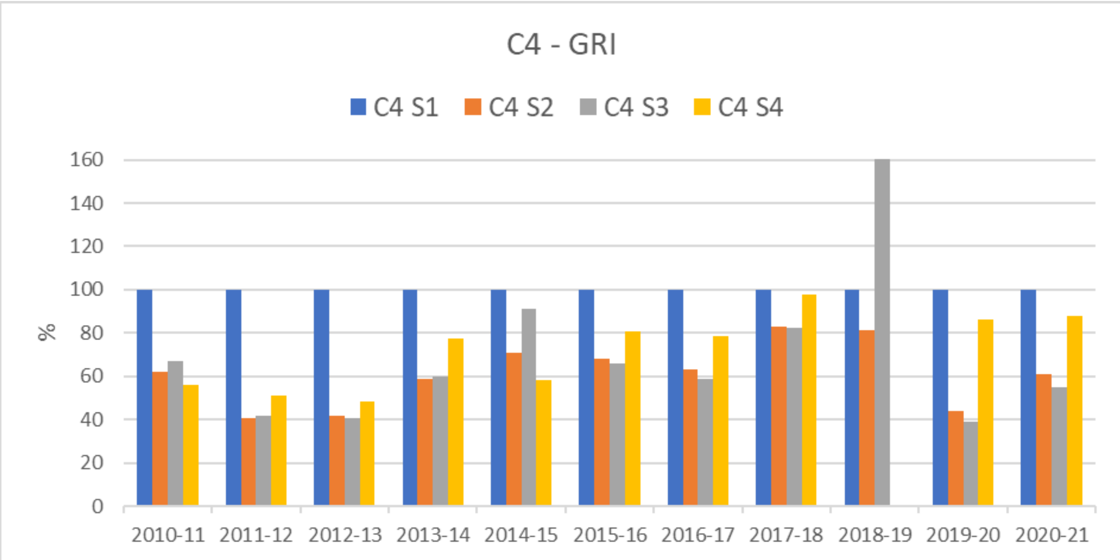


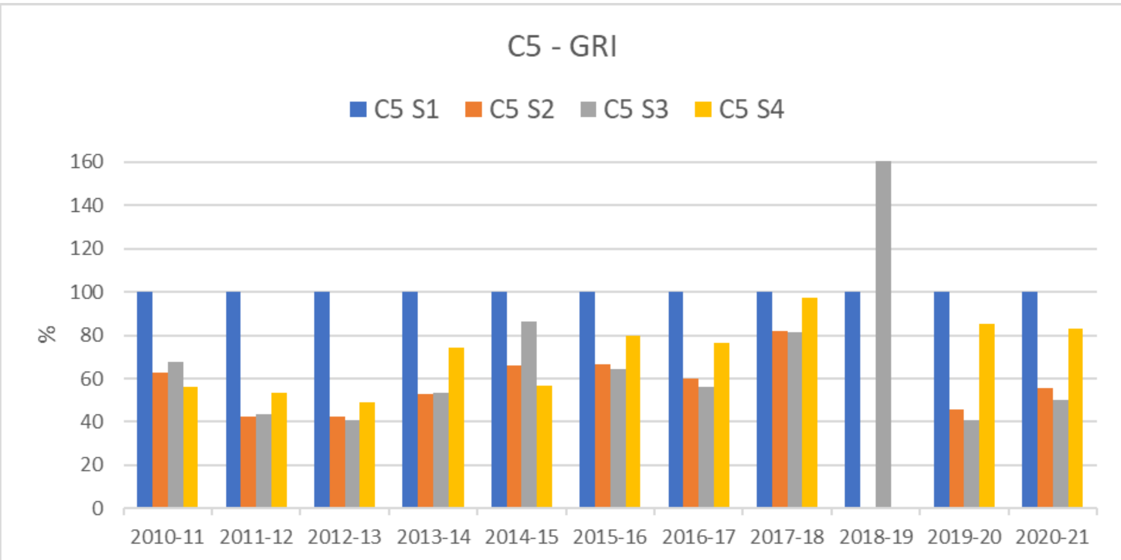
Appendix D.3 Groundwater Recharge Index

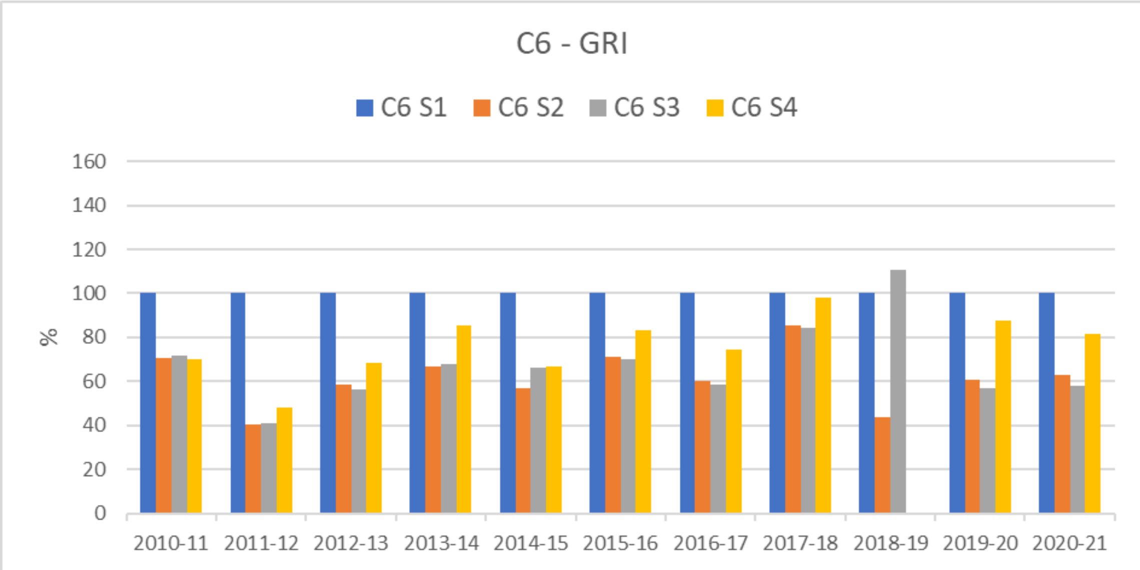


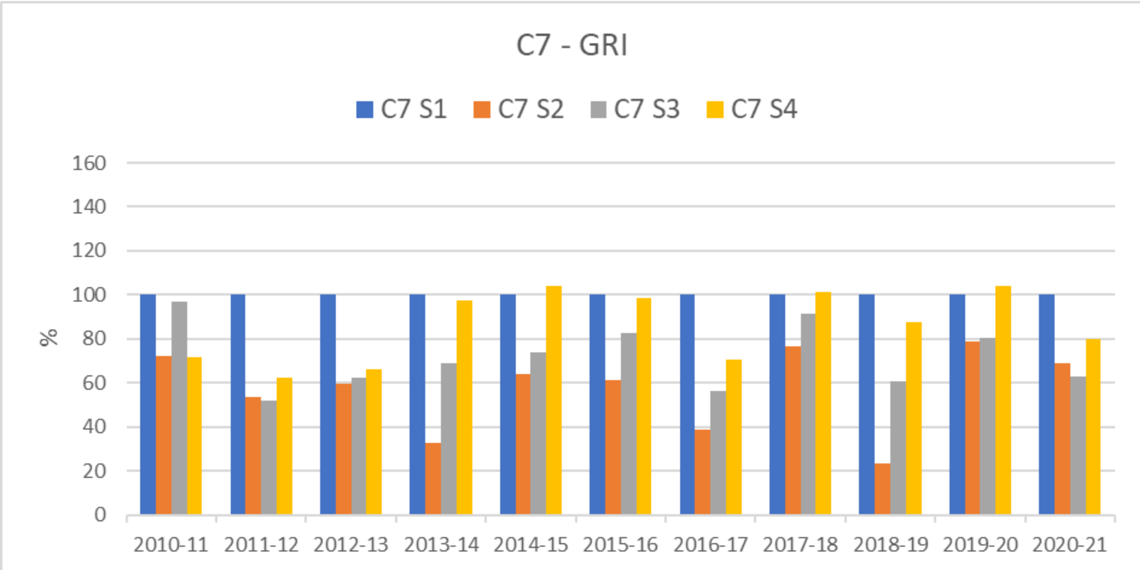


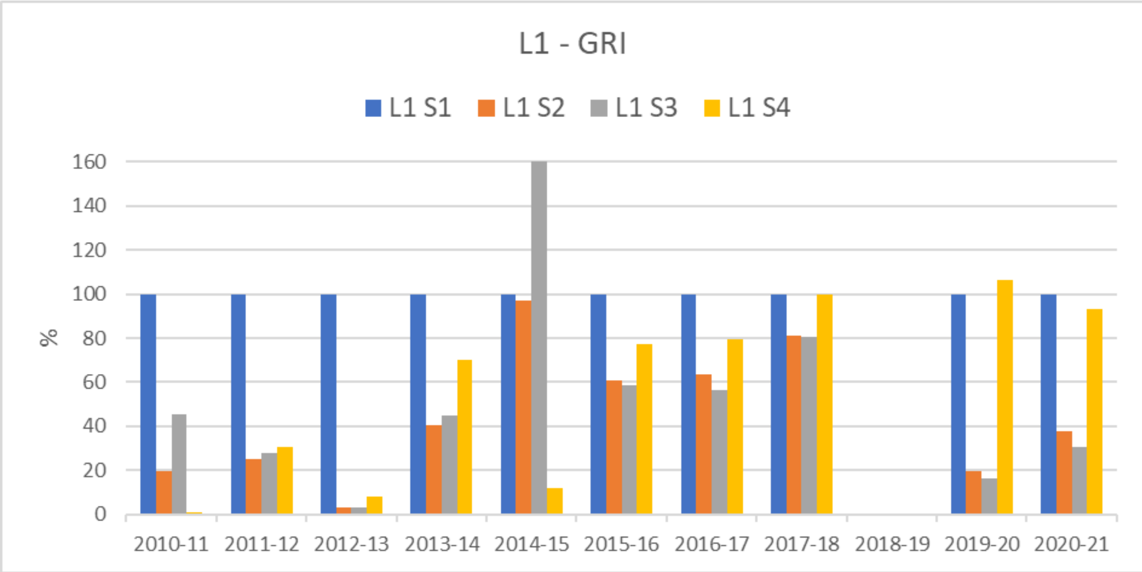

C3 - GRI
C3 S1
C3 S2
C3 S3
C3 S4
%
0
20
40
60
80
100
120
140
160
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21

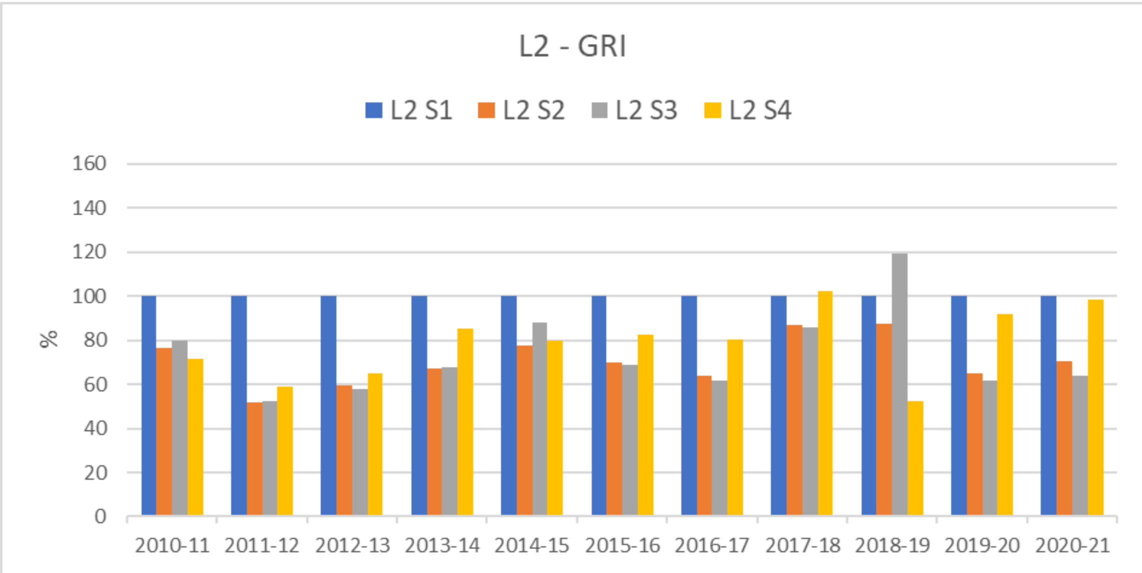

C4 - GRI
C4 S1
C4 S2
C4 S3
C4 S4
%
0
20
40
60
80
100
120
140
160
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21


C5 - GRI
C5 S1
C5 S2
C5 S3
C5 S4
%
0
20
40
60
80
100
120
140
160
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21

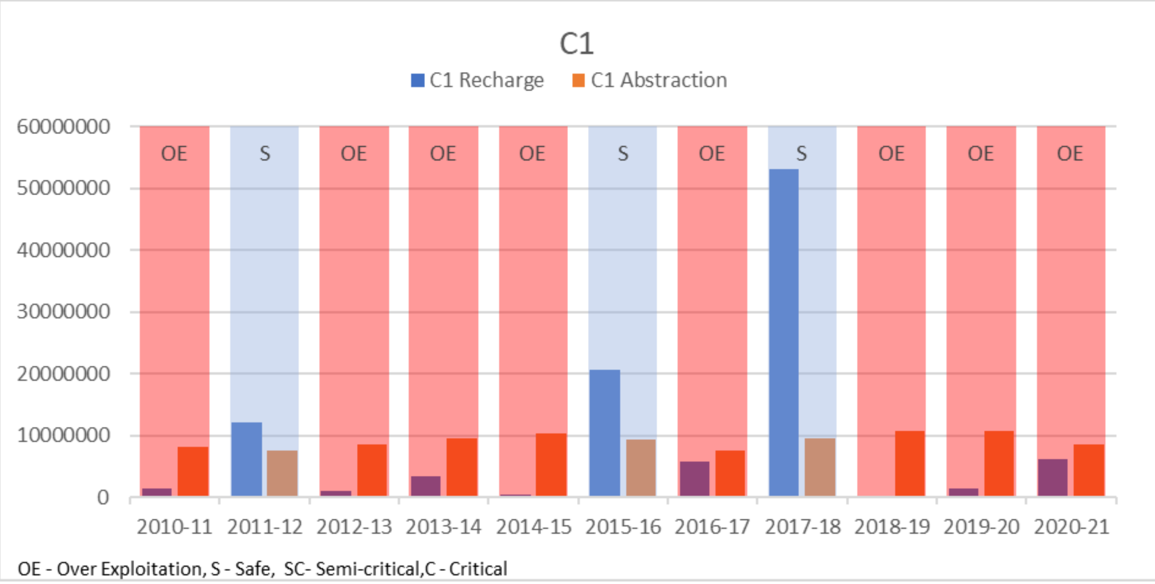

C6 - GRI
C6 S1
C6 S2
C6 S3
C6 S4
160
140
120
100
80
60
40
20
0
%
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21

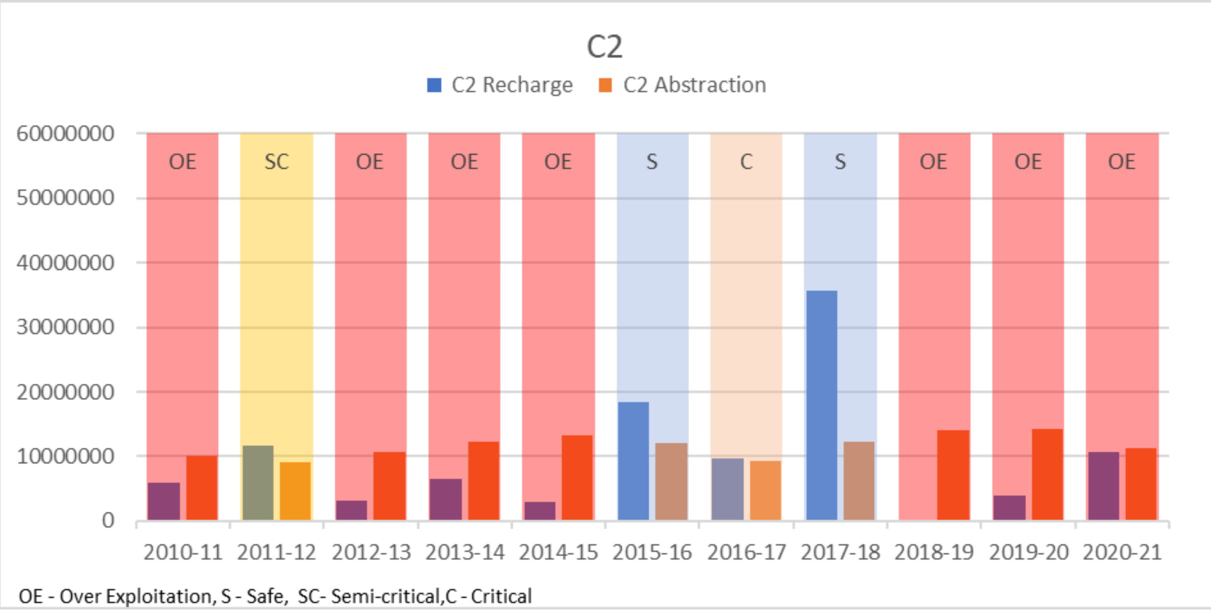

C7 - GRI
C7 S1
C7 S2
C7 S3
C7 S4
160
140
120
100
80
60
40
20
0
%
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21

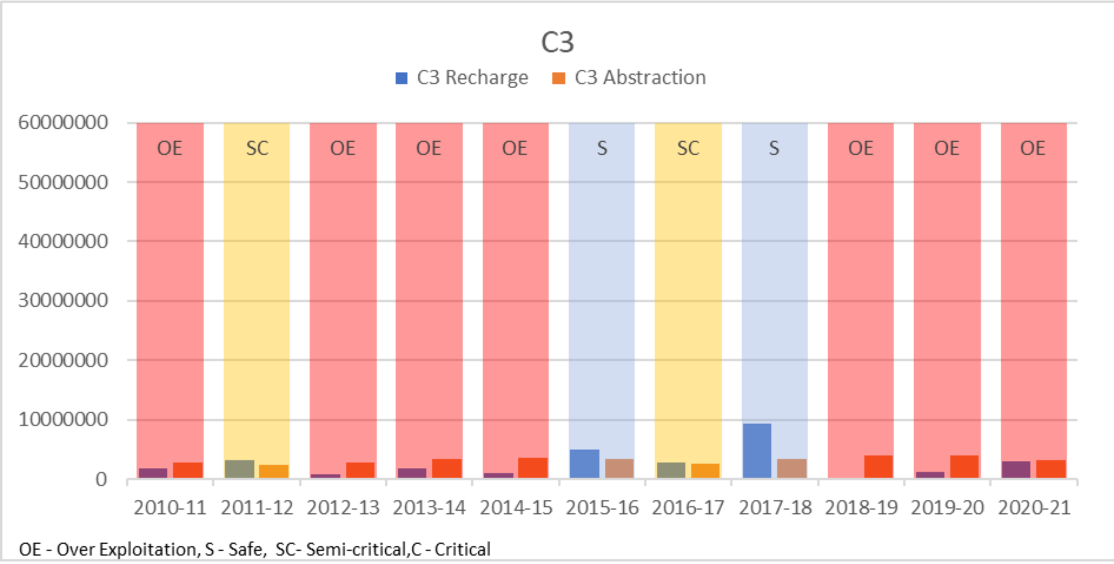

L1 - GRI
L1 S1
L1 S2
L1 S3
L1 S4
160
140
120
100
80
60
40
20
0
%
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21

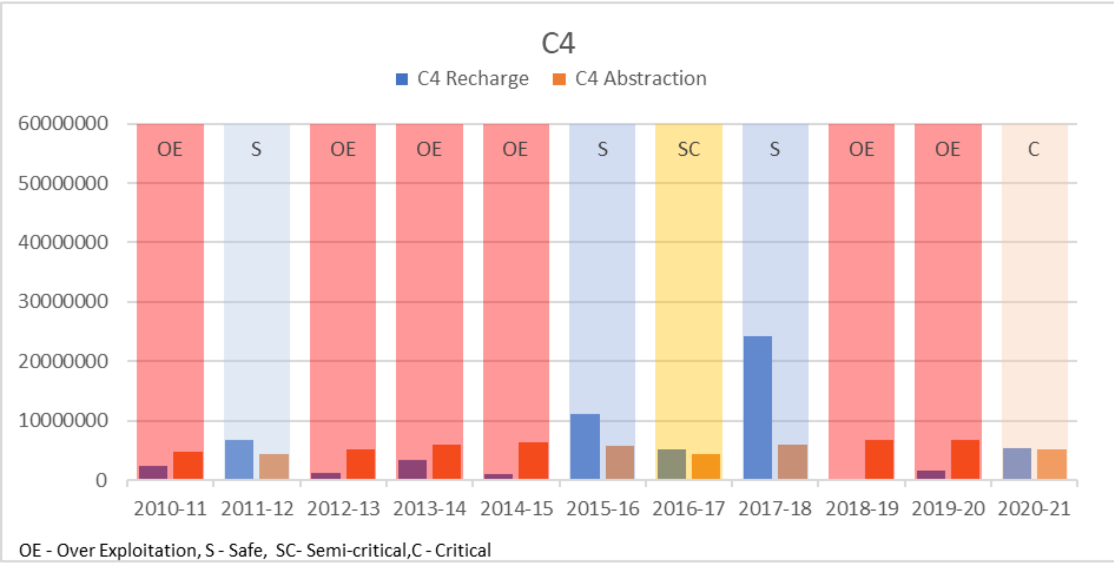

L2 - GRI
L2 S1
L2 S2
L2 S3
L2 S4
160
140
120
100
80
60
40
20
0
%
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21

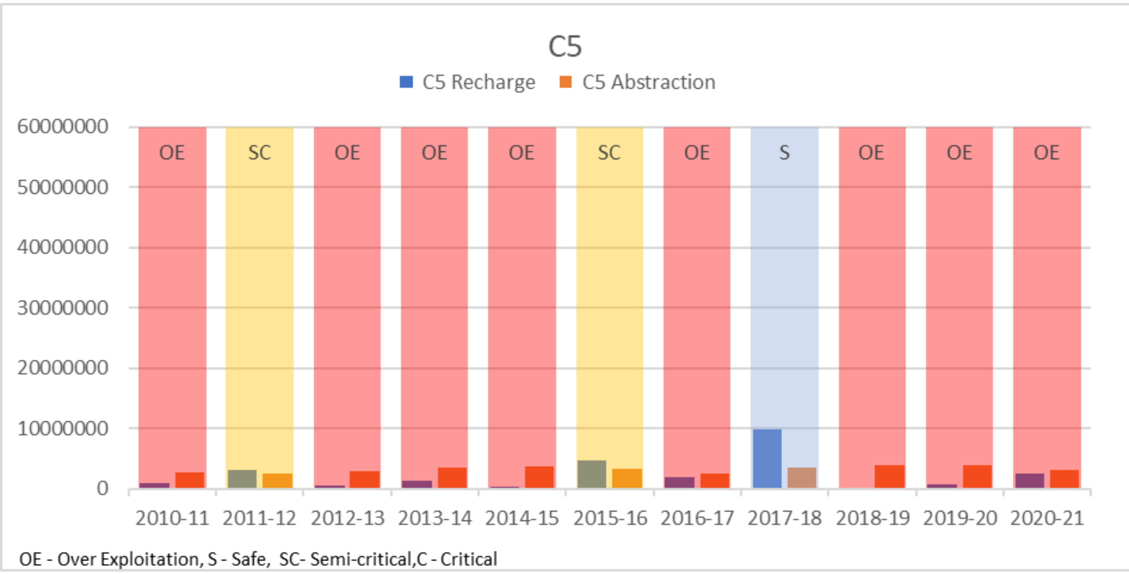
Appendix D.4 Critical/ stressed groundwater






C3
C3 Recharge
C3 Abstraction
60000000
50000000
40000000
30000000
20000000
10000000
0
OE
SC
OE
OE
OE
S
SC
S
OE
OE
OE
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21
OE - Over Exploitation, S - Safe, SC- Semi-critical,C - Critical


C4
C4 Recharge
C4 Abstraction
60000000
50000000
40000000
30000000
20000000
10000000
0
OE
S
OE
OE
OE
S
SC
S
OE
OE
C
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21
OE - Over Exploitation, S - Safe, SC- Semi-critical,C - Critical


C5
C5 Recharge
C5 Abstraction
60000000
50000000
40000000
30000000
20000000
10000000
0
OE
SC
OE
OE
OE
SC
OE
S
OE
OE
OE
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21
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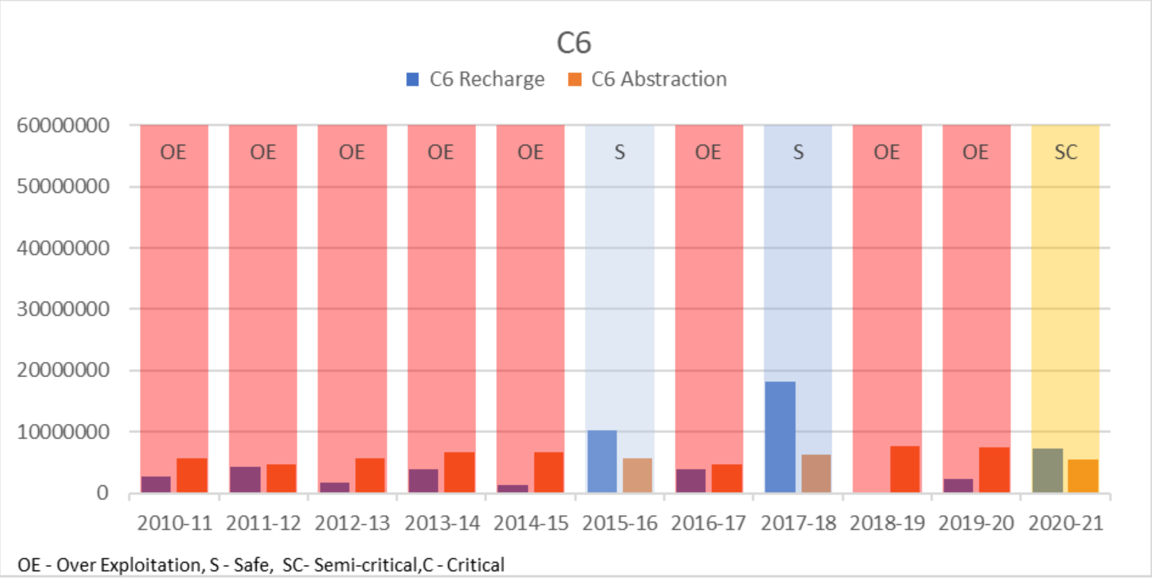
C6
C6 Recharge
C6 Abstraction
60000000
50000000
40000000
30000000
20000000
10000000
0
OE
OE
OE
OE
OE
S
OE
S
OE
OE
SC
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21
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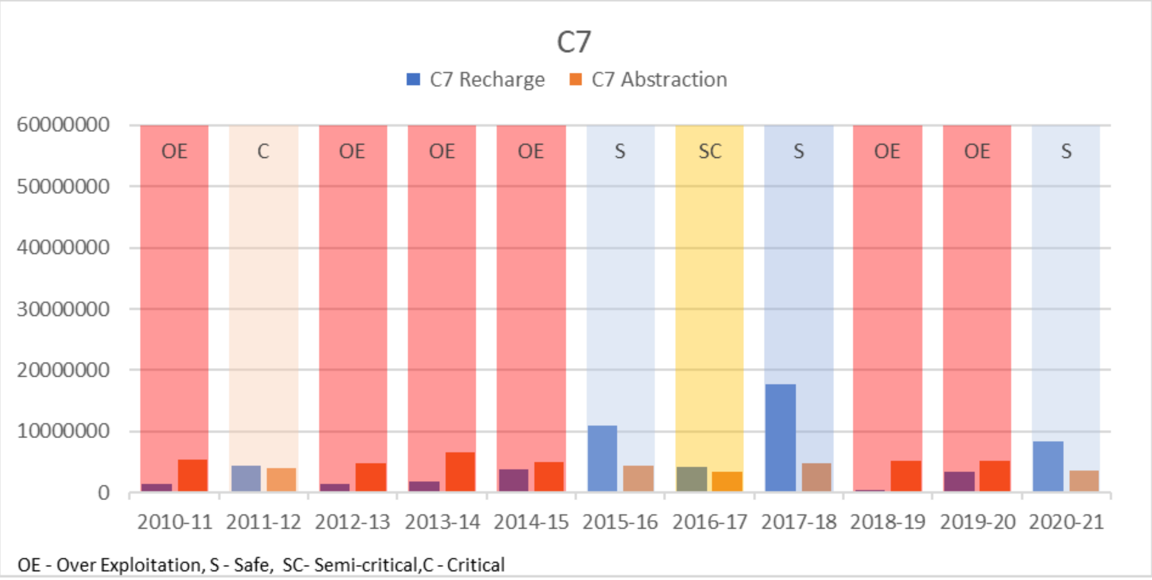
C7
C7 Recharge
C7 Abstraction
60000000
50000000
40000000
30000000
20000000
10000000
0
OE
C
OE
OE
OE
S
SC
S
OE
OE
S
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21
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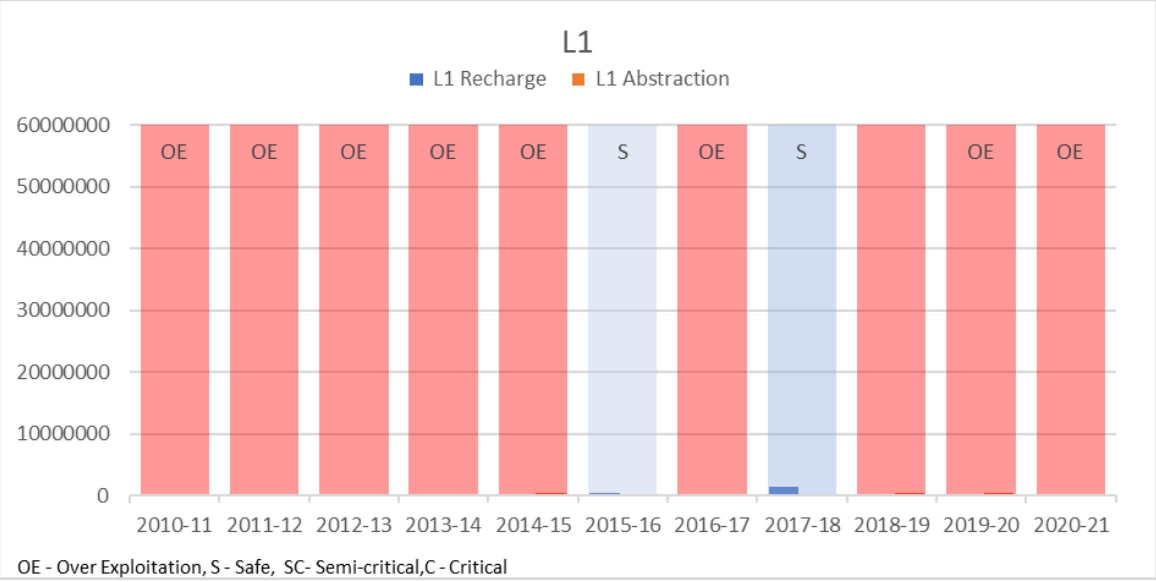
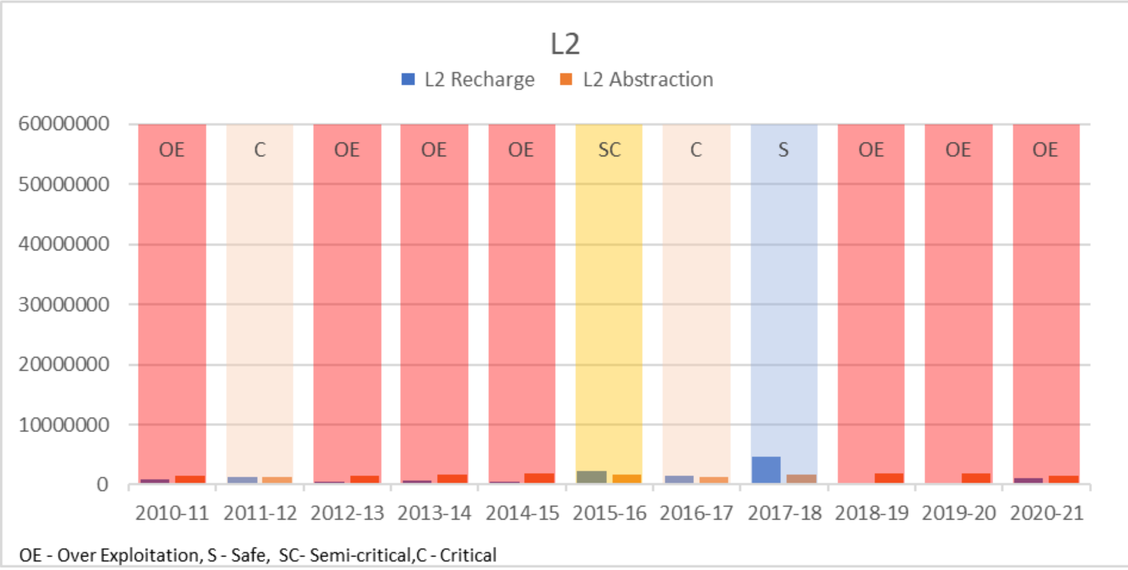

L1
L1 Recharge
L1 Abstraction
60000000
50000000
40000000
30000000
20000000
10000000
0
OE
OE
OE
OE
OE
S
OE
S
OE
OE
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21
OE - Over Exploitation, S - Safe, SC- Semi-critical,C - Critical


L2
L2 Recharge
L2 Abstraction
60000000
50000000
40000000
30000000
20000000
10000000
0
OE
C
OE
OE
OE
SC
C
S
OE
OE
OE
2010-11
2011-12
2012-13
2013-14
2014-15
2015-16
2016-17
2017-18
2018-19
2019-20
2020-21
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