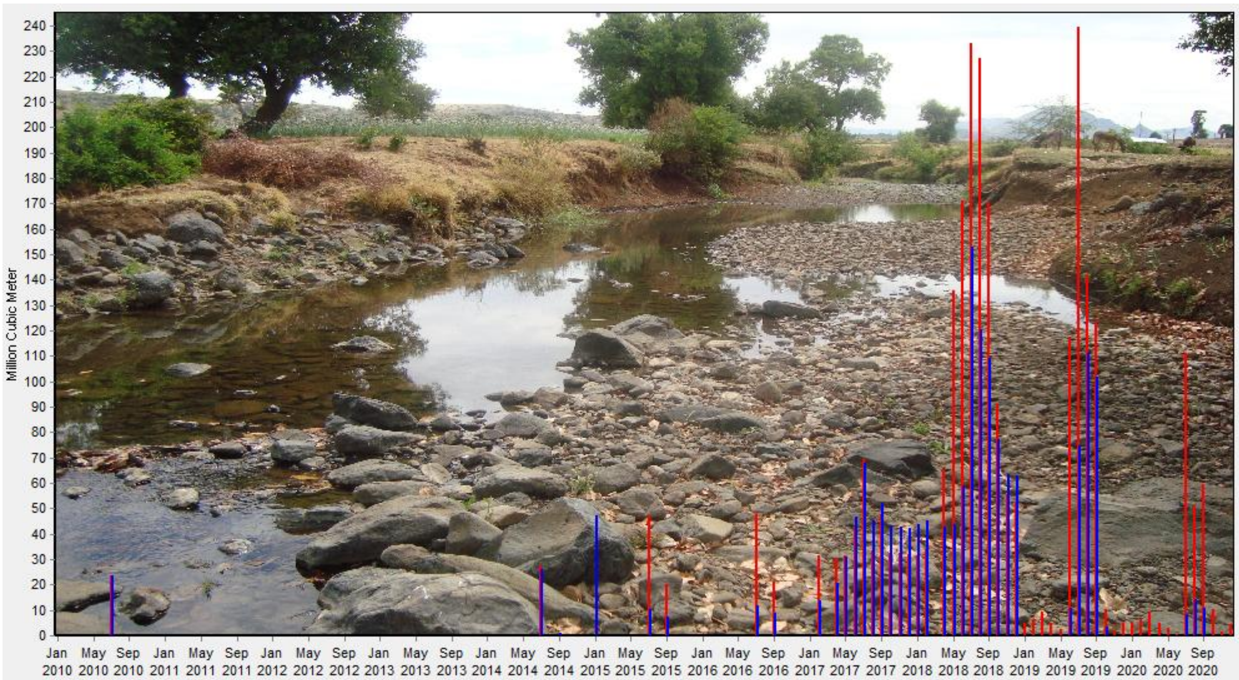
Water Evaluation and Planning (WEAP) tool for water resource management



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Contents

Acronyms

BOD	Biochemical Oxygen Demand
CRSS	Colorado River Simulation System
DHI	Danish Hydraulic Institute
DO	Dissolved Oxygen
DSS	Decision Support Systems
GIS	Geographic Information System
GWP	Green Water Project
INBO	International Network of Basin Organizations
IRAS	Interactive River Aquifer Simulation
IWMI	International Water Management Institute
IWRM	Integrated Water Resource Management
LRS	Long Range Study
PRISM	Potomac River Interactive Simulation Model
SDSS	Spatial Decision Support Systems
SEI	Stockholm Environmental Institute
SHE	European Hydrological System
SWIM	System-Wide Initiative on Water Management
TERRA	Tennessee Valley Authority's Environment and River Resource Aid
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
UN-Water	United Nations mechanism for coordination of all water related issues
USA	United States of America
WEAP	Water Evaluation and Planning tool
WWTP	Waste Water Treatment Plants

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Acknowledgements

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EXECUTIVE SUMMARY

Water is an essential natural resource upon which all life and almost all sectors of any economy depend. Ensuring that all the water demand is equitably, efficiently and sustainably met by the existing supply sources within a water management system is a critical component of any water management project. Additionally, the quality of water supplied to various users within the water management system should be guaranteed and at the same the ecosystem integrity of the surrounding landscape should also be maintained. As a result of the many users and aspects that should be considered when carrying out water resource management projects, a holistic approach that looks at demand side issues in the context of supply side issues should always be considered.

Different models have been designed to simulate different aspects of water resource management. Similarly, a variety of models have also been developed to optimize water resource management processes based on specific project objectives. Water Evaluation and Planning (WEAP) is an integrated water resource management tool developed by Stockholm Environmental Institute (USA). It implements an integrated approach by placing water supply projects in the context of demand side issues, quality and ecosystem preservation.

Within WEAP, a model "river basin" is created with different nodes representing the source components, the demand side components and the intermediate links between the source and the demand sides. The parameters for these components can then be defined and used to simulate different aspects of the "river basin". The tool also takes advantage of Geographic Information Systems (GIS) in defining spatial relationship between the different elements of the water management system.

The general aim of this study was to demonstrate how to create a water management system of within the WEAP tool and the implementation of various scenarios within the tool. In particular the impact of population change and the impact of climate change were assessed using hypothetical datasets within the WEAP tool. Results from the tool can be used to make decisions regarding various water management system elements and also to gain knowledge on the policy frameworks that can be implemented to ensure sustainable use of the available water resources under different changing scenarios.

1.0 Introduction

Water is an essential substance upon which all life depends (UNESCO, 2011), it is also a key driver of economic and social development while it also has a basic function in maintaining the integrity of the natural environment (UN-Water, 2008). Even though water accounts for three quarters of the earth surface, not all this is available for human consumption (UNESCO, 2011); in fact 99% of the water available in oceans, ice and atmospheric water is not available for human use. Further still much of the remaining water is stored in the ground and thus only leaving approximately 0.0067% in the surface sources including rivers and lakes (UNESCO, 2011). This scarcity in the amount of water resources available for human consumption therefore calls efficient use of the available resources. There is also a great difference in the availability of water resources from region to region with extreme situations in the deserts and sufficient availability in the tropical forests (UN-Water, 2008). Further still even the quality of the available water resources is not guaranteed due to impurities resulting from pollution due poor land use practices and poor waste management around the water resources. It is on this background that the concept of water resource management then becomes vital in ensuring that the available water resources are efficiently utilized while at the same time ensuring that the quality of water the available water resource is fit for human consumption.

1.1 Integrated water resource management

Apart from the domestic water uses, there is an even greater demand for water for industrial, agricultural and in the energy sectors (hydro power stations and cooling of thermal and nuclear power stations) among others. Apart from utilizing water resources, these users also affect the quality of the water resources either by pollution or by their methods of abstraction. The impact of such influences is felt by the downstream users and also in the natural ecosystems (UN-Water, 2008). Water resources management therefore aims at optimizing the available natural water flows, including surface water and groundwater, to satisfy the competing needs (World Bank, 2012) while ensuring that the quality of the water resources is not compromised. In order to put integrated water resource management in a proper context, three key principles should be considered (WaterAid in Nepal, 2011). These principles include the following:

- Water and sanitation sector is affected by water use in other sectors
- There are potential positive and negative impacts of all the water uses, due to the interconnectedness among the uses of the resources, particularly in the catchment scale.
- There is need for a holistic view, to ensure equitable and efficient use of water.

Based on these key principles, Integrated Water Resource Management (IWRM) has been defined as a process which promotes the coordinated development and management of water, land and related resources in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystem (GWP, 2000). The integrated water resources management approach helps to manage and develop water resources in a sustainable and balanced way, taking account of social, economic and environmental interest (GWP and INBO, 2009).

1.2 River basin concepts of water resource management

In the context of water resource management, a typical river basin is made up of three main components (McKinney et al, 1999);

i. Source components such as rivers, canals, reservoirs and aquifers
ii. Demand components which comprise of both off-stream (irrigation fields, industrial sites, and cities) and in-stream (hydro-electric power stations, recreation and environmental) components
iii. Intermediate components such as treatment plants and water reuse and recycling facilities.

The figure 1 below shows a schematic diagram of the different components of a river basin. In summary the diagram consists of supply system (ground water systems, river reaches and reservoirs), the delivery system, demand side components (agricultural, municipal, and industrial) and the drainage collection system (surface and subsurface). Atmospheric influences on the river basin such us evapotranspiration and human influences such as diversion and anthropogenic land use changes can also be factored in to the schematic view. A comprehensive water resource modeling for a river basin therefore should not only include the physical and natural processes in the basin but also the human initiated projects in the basin and the policy framework that are put in place to regulate different system elements (McKinney et al, 1999). An ideal model should also include a sub-model that is specifically dedicated to modeling the changes in human behavior in response to different policy initiatives. Examples of these can include sub-models that can be used to analyze the changes in water resource demand as a result of changes in the cost of water or the changes in water use resulting from technological changes. In an integrated approach, the relationships within individual components and the interrelationship between different components within the river basin should also be considered.

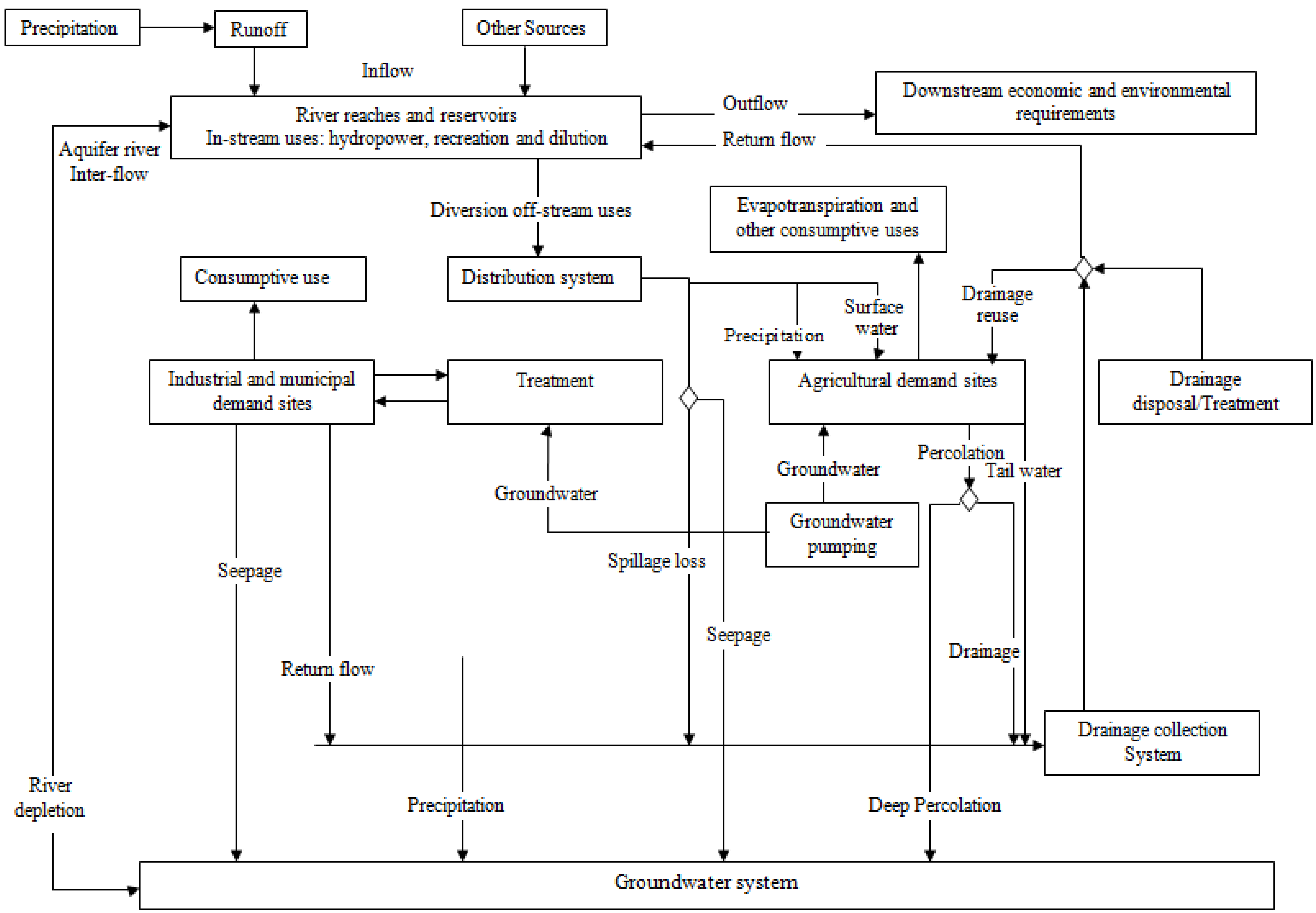


Figure 1: Schematic representation of river basin processes (Adapted from McKinney et al, 1999)

1.3 Models for water resource management

Water management generally involves development, regulation and beneficial use of surface and underground water resources (Wurbs, 1994). This is done by first and foremost identifying the services that should be provided by the water management community. Generally some of the services that should be within the command of the water management community include: water supply for agricultural, industrial and municipal uses; waste water collection and treatment; protection and enhancement of environment resources; pollution control; storm water drainage; flood control and flood water drainage to reduce the impact of floods; hydroelectric power generation among other services.

Once the services have been identified, the water management community should come up with the plans that will ensure that the available water resources are used sustainable and equitably so that the water needs of all the users are satisfactorily met. In this respect, the water resource planning and management activities involve: formulation of policies; resource assessment at national, regional and local levels; regulating and permitting functions; formulation and implementation of resource management strategies; planning, design, construction and maintenance of the necessary infrastructure; research, education and training on matters related to the water resource management (Wurbs, 1994).

With the advent of computers, different models have been designed for almost every aspect of the water resource management. However before utilizing any model for water resource planning and management, it is prudent to have a thorough understanding of the following requirements (Wurbs, 1994):

- The role of the model in the planning and management process and the particular questions that the modelling processes are meant to answer.
- The real world situations and the limitations of the different mathematic equations that are used to represent these situations within the model.
- Data needs for the models; this is closely related to the data availability and limitations.
- Model calibration and validation
- Availability of the necessary computer software to run the model (with the necessary licenses) and the necessary skills needed to use the software.
- Communication capabilities required to ensure that the model development and application are responsive to the water resource planning and management needs and that the model results are effectively incorporated into the decision making process.

Most water resource management projects include economic, environmental and social considerations of the particular project under consideration. Additionally, computer-based models are used since they can aide in clarifying trade-offs within the systems under consideration and also help in identifying the plans, designs and policy options that limit undesired impacts of the project while maximizing the desired impacts (Loucks, 2008).

There are two broad categories of computer-based models for water resource management, these are; simulation models and optimization models (Loucks, 2008). Simulation models tend to address "what if" questions in the analysis process. Given different assumptions for system design and operation, simulation models can predict how the system will perform in with the different assumptions (scenarios). In other words, simulation models tend to replicate water resource behavior based on predefined set rules (which can either be actual or hypothetical) governing water allocation and infrastructure operation (McKinney et al, 1999). Optimization models on the other hand address "what should be questions", that is, what design and operating policy options will best meet the system objectives. Since the algorithms used to solve optimization models tend to limit the number of assumptions (details) that can be included in the system model, optimization models are normally used to filter out unsatisfactory alternatives within a complex system (Loucks, 2008), simulation models can then be used to investigate the remaining more promising alternatives.

1.4 GIS and water resource management models

Geographic Information System (GIS) is a general-purpose technology for handling geographic data in digital form. Its abilities include; preprocessing of data to a form that is suitable for spatial analysis, spatial data storage, analysis and modeling, post-processing and presentation of results in both digital and hard copy (paper) formats (McKinney & Ximing, 2002). In the context of water resource management, GIS can be used for spatial representation of the water management system and to bring spatial dimensions to traditional water resource databases. This can be accomplished by including the economic, social and environmental factors related to the spatial entities of water resources problems into a single GIS database and availing these for use in decision making for the water resources under consideration.

Additionally the visual display capability of most GIS systems complements the user interface of the water resource systems (McKinney & Ximing, 2002). Further still, GIS tools are also useful for carrying out 2 dimensional and 3 dimensional spatial calculations such as in watershed boundary delineation, delineation of stream paths and in the modeling of distributed runoff (Loucks, 2008). In order to take advantage of GIS in water resource management and planning, water related mathematical models can be implemented within the GIS platform. Looked at in another way, a combination of GIS and water resource simulation models can greatly improve the understanding of water resource related issues (Wilson et al, 2000). Further still, the power of applying GIS in water resource modeling comes in its ability to combine different datasets including Digital Elevation Models, land cover data, soil data, climate data, river and stream path data among others. Additional other anxilliary data sets including economic, social and environmental data can also be geo-coded and integrated in the modeling process.

1.5 Evolution of water resource management models

McKinney et al, 1999 looked at the evolution of river basin water management simulation models, in particular they pointed out that the advent of computers and further improvements in the computer software and hardware has played a major role in the evolution of water resource simulation models and in the complexity of the aspects of water resources that such models can be used to analyze. In their study, they looked at four broad categories of water resource simulation models which include:

i. River basin flow simulation models: Some of the models reviewed in this category included the Long Range Study (LRS) model for Missouri River, Potomac River Interactive Simulation Model (PRISM), Colorado River Simulation System (CRSS), and AQUATOOL which integrates simulation, risk, optimization and groundwater analyses.

ii. River basin quality simulation models: Water quality simulation is a standard feature of most river basin simulation models, some of the elements of water quality that are considered in such models include temperature, dissolved oxygen (DO), biochemical oxygen demand (BOD). The main models which were looked at in this category included; Enhanced Stream Water Quality model QUAL2E which is distributed by United States Environmental Protection Agency (EPA). QUAL2E simulates temperature, DO, BOD, chlorophyll A, nitrogen (organic N, ammonia NH3, and nitrate NO3-), phosphorus (P, organic and inorganic), and coliforms in addition to constituents with user defined decay properties. The other model that was looked at in this category was the Water Quality for River-Reservoir Systems (WQRRS) which was developed by United States Army Corps of Engineers, Hydrological Engineering Centre. The model simulates DO, total dissolved solids, P, NH3, NO2-, NO3-, alkalinity, total carbon, organic constituents, and a range of aquatic biota.

iii. River basins water rights simulation models: These are models that are used to simulate water resource allocation to various users based on the prevailing system of water rights within the river basin.

iv. Comprehensive river basin simulation systems: These are interactive models that combine the models defined above and are accompanied by graphical user interfaces for ease of manipulation by users. The earliest examples of these models are the Interactive River Aquifer Simulation (IRAS) model which introduced advanced graphical capabilities for all the stages of simulation. IRAS models were used to simulate flow, storage, water quality, hydropower and energy for pumping. The other examples are the

Tennessee Valley Authority's Environment and River Resource Aid (TERRA) model which was designed as a reservoir and power generation operations tool kit.WaterWare is another comprehensive river basin simulation model which was designed by a consortium of European Union countries for demand forecasting, water resource planning, groundwater and surface water pollution. WaterWare model also has GIS components that allow for import of GIS layers in different formats. The final model discussed in this category was the European Hydrological System (SHE) which was developed as a distributed and a physically based modeling system for describing major flow processes of the entire land phase of a hydrological cycle (McKinney et al, 1999). Variations of this model are the MIKE SHE model and MIKE BASIN model which is developed by the Danish Hydraulic Institute (DHI).

Apart from the models described above, several other alternative models have been developed which do not necessarily fit strictly into a single category, but possess characteristics from a variety of categories. One of such models is the Water Evaluation and Planning (WEAP) tool which was developed by Stockholm Environmental Institute (USA). WEAP is mainly a simulation model with two primary functions (Sieber et al, 2005) which are; (1) Simulation of natural hydrological processes (e.g., evapotranspiration, runoff and infiltration) to enable assessment of the availability of water within a catchment (2) Simulation of anthropogenic activities superimposed on the natural system to influence water resources and their allocation (i.e. consumptive and non-consumptive water demands) to enable evaluation of the impact of human water use.

In addition to the two the primary functions of the WEAP tool, it is also designed to interact with (and is actually installed with) other water resource models including MODFLOW, MODPATH, QUAL2K and PEST. While MODFLOW and MODPATH are models for simulating groundwater flow and particle path respectively, the QUAL2K model can be used to simulate water quality while PEST is used for parameter estimation and can be used to calibrate and validate the results from WEAP model based on historical data. This interaction between WEAP model and other models therefore gives it the ability to be used for simulating the effect of different scenarios on quantities (water supply and demand), water quality, costs and the ecosystem integrity of water management system under consideration. In this study a review of some of the key elements of the WEAP tool and a demonstration on how it can be implemented in water resource projects is presented. An elaborate description of the various elements of the WEAP tool is given in the subsequent section of this report.

1.6 Water Evaluation and Planning (WEAP)

WEAP is a microcomputer tool for water resource planning (Sieber, 2006), it implements an integrated approach that places water supply projects in the context of water demand-side issues, water quality and ecosystem preservation. WEAP places the demand side of the equation on the same footing as the supply side and allows the user to examine various alternatives to water development and management strategies (Sieber, 2006). The tool allows the user to implement various "what if" analysis, by setting various scenarios for the various components of the analysis either on the demand or the supply side. The result of the various scenarios can be viewed simultaneously thus facilitating easy comparison of the effects of the various scenarios to the water system. Apart from giving information on the quantity and quality of water, the system also allows for input of the monetary costs involved in setting up and maintenance of different system components.

1.6.1 WEAP program structure

WEAP tool is structured in five main views which are; schematic view, data view, results view, overview (scenario) view and the notes view.

a) Schematic view

This view consists of GIS tools that can be used to configure the water management system (the model of the river basin) under consideration. Icons for various drainage system components are incorporated on to the view and these can be used to create various systems elements by simply dragging and dropping the respective icons on the appropriate location on a georeferenced map. Some of the components of the system that are included in this view include rivers, diversions, reservoirs, ground water aquifers, local supply points, demand sites, transmission links, waste water treatment points and the flow requirements. Other GIS layers including vector and raster format layers can be added as background layers, mainly for referencing. The attribute tables of the added GIS layers can be viewed, their symbols can also be varied and the view also has tools which can be used for labelling the input vector layers. This is important since the labels can be used to guide the system design process. Finally the data representing the designed water management system on the schematic view can be saved in kml (Keyhole Mark-up Language) format and viewed on Google Earth platform. This is important especially when the information is to be shared with other stakeholders to visually confirm the design of the water management system under consideration. The figure 2 below is a screen shot of the schematic view on which county borders, drainage lines and town have been added. On the second row on the left side of the view are the icons which can be used to create different system elements.

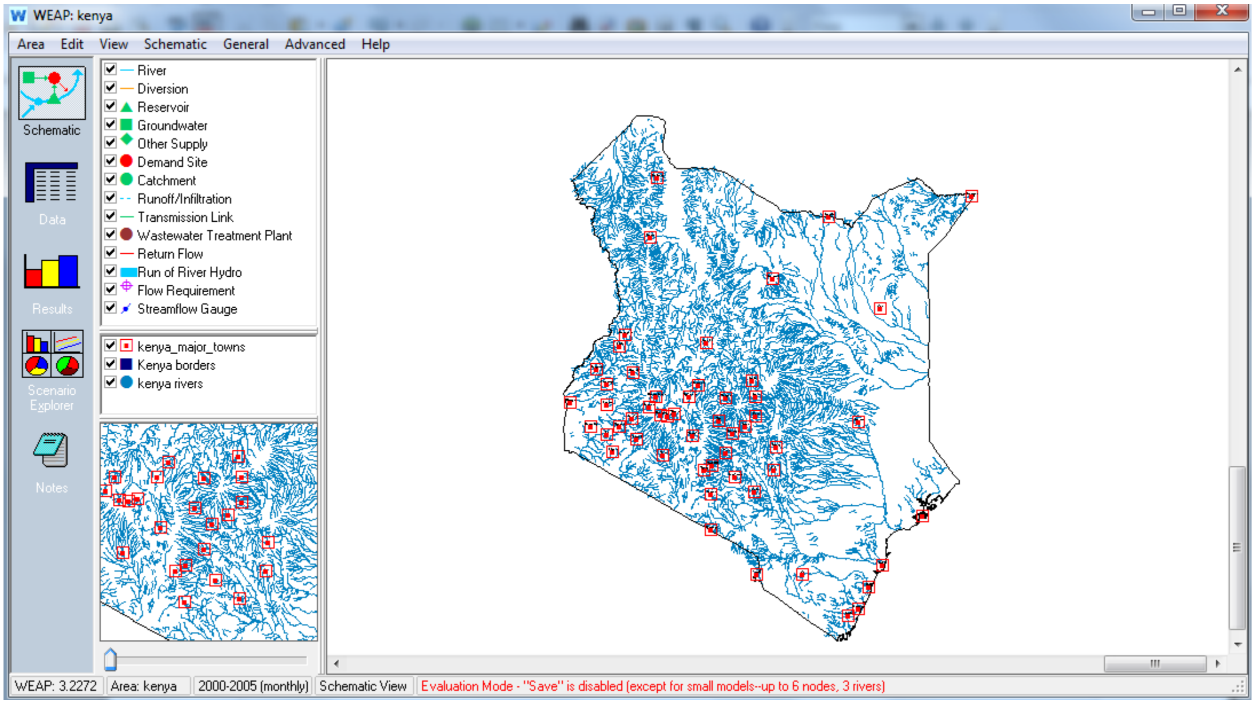


Figure 2: Schematic view on WEAP

b) Data view

This is the view where all the system data is modelled and the system variables can be defined. The view enables various assumptions about the system to be made and for the necessary projections to be carried out by using mathematical equations. Since the results that are ultimately obtained from the model heavily depend on the data that is input into the model, time should be spent to correctly and extensively define the data and parameters that relate to the system under consideration.

The kind of data and variable that should be included in the system include (but is not limited to), the historical water supply into the system, the water supply infrastructure, water storage capacity of various storage elements, the costs involved in setting up and maintenance of different infrastructure, users of water resources within the system, unit cost of water, the likely changes in supply and demand, the quality related parameters among others. It is important to note at this point that the WEAP tool is installed with default parameters which are very elaborate and should lead to acceptable results, however, users can also add their own parameters which their deem relevant for their analysis.

Data can either be typed into the system one by one into the system or the data view can be dynamically linked to Microsoft Excel files to import formatted data into the system or to export data out of the system.

c) Results view

This view allows for detailed presentation of all model outputs either as graphical layers or in tabular formats. Results from every aspect of the system can be displayed; these may include details on demand, supply, costs and environmental inputs into the system. The view allows the user to zoom in to the results of any system element as long as the element was included in the analysis.

d) Overview or scenario explorer

The scenario explorer view allows the user to design and display various unique outputs from each aspect of the system in this way, it allows one to have a birds' eye view of the various highlights of the system.

Scenario analysis is central to WEAP. Scenarios are used to explore the model with an enormous range of "what if" questions (WEAP User guide 2005), including but not limited to the following:

- What if population growth and economic development patterns change?
- What if reservoir operating rules are altered?
- What if groundwater is more fully exploited?
- What if water conservation is introduced?
- What if ecosystem requirements are tightened?
- What if new sources of water pollution are added?
- What if a conjunctive use program is established to store excess surface water in underground aquifers?
- What if a water recycling program is implemented?
- What if a more efficient irrigation technique is implemented?
- What if the mix of agricultural crops changes?
- What if climate change alters demand and supplies?

e) Notes view

The notes view allows the user to document and to maintain a record of data specifications and various assumptions that have been incorporated into the system. These records can then be accessed by any future users of the system in order to understand the assumptions that were factored into the system and the details of each system component.

1.6.2 Watershed system elements in WEAP

WEAP tool is designed with ready-made key watershed system components which the user can add to the area under consideration depending on the components which are available in the area. In the WEAP tool graphical user interface, these components are represented with icons which can simply be clicked on and dragged to the appropriate locations on the schematic view.

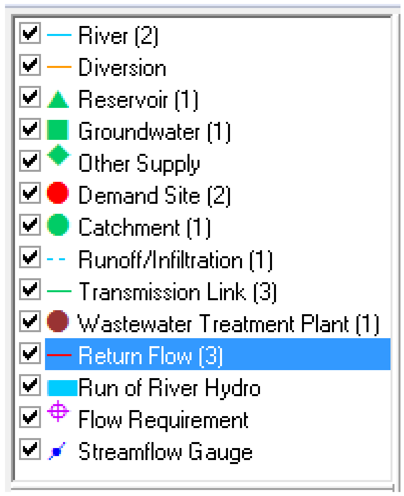


Figure 3: Icons for water system elements within WEAP tool

Key among these elements are elaborated below

i. Demand Sites

This is a set of users that share a physical distribution system, that is, a set of users that may be from the same geographic region or share the same node for withdrawing their water needs. Since it is difficult to get data on every single user, a group of users from the same locality for instance a city or an estate can be considered as a demand site. Their demand needs are aggregated and assigned to the representative demand site. The number, type and spatial extent of users that can be considered to belong to a single demand site however depend on the purpose of the analysis and the kind of accuracy expected from the modelling exercise.

When deciding to place a demand site, a detailed inventory of the available water management infrastructure should be considered to ensure that there is a proper link between the demand and supply nodes. Each demand site should be linked to its source of water and where possible, a return link to a river or to the waste water treatment plant from the demand site in question.

ii. Catchments

These are the points that are created in the schematic view of the water management system to account for the effects of precipitation, evapotranspiration, irrigation, runoff and sediment yields in both agricultural and non-agricultural fields within the system. In order to accurately place catchment nodes, relevant elevation and land use/ land cover data should be used as references.

iii. Rivers, diversions and river nodes

Both rivers and diversions in WEAP tool are made up of river nodes connected by river reaches. It is possible to have other rivers flowing into (tributaries) or out (diversions) of a river. There are seven types of river nodes (WEAP user guide 2005) which can be included in the system, these are;

- **Reservoir** nodes, which represent reservoir sites on a river and can release water directly to demand sites or for use downstream and also can be used to simulate hydropower generation.
- **Run-of-river hydropower** nodes, which define points on which run-of-river hydropower stations are located.
- **flow requirement** nodes, which define the minimum in stream flow required at a point on a river or diversion to meet water quality, fish & wildlife, navigation, recreation, downstream or other requirements.
- **Withdrawal** nodes, which represent points where any number of demand sites receive water directly from a river.
- **Diversion** nodes, which divert water from a river or other diversion into a canal or pipeline called a diversion. The diversion is itself, like a river, may be composed of a series of reservoirs, run-of-river hydropower plants, flow requirements, withdrawals, diversions, tributaries and returns flow nodes.
- **Tributary** nodes define points where one river joins another. The inflow from a tributary node is the outflow from the tributary river.
- **Return flow** nodes, which represent return flows from demand sites and wastewater treatment plants. Return flows may also enter the river at any type of river node: reservoir, run-of-river, tributary, diversion, flow requirement, withdrawal, or return flow node.

iv. Stream flow gauges

Stream flow gauges are placed on river reaches and represent points where actual stream flow measurements have been acquired and can be used as points of comparison to simulated flows in the river.

v. Ground water

These are nodes representing ground water sources and aquifers and can either have natural inflows, or be recharged by catchment infiltration or from the returns from a demand site or a waste water treatment plant. The groundwater nodes can be connected to many demand sites.

Apart from these elements, there are transmission links which are used as conduits for water between water sources and the demand sites. Additionally there are return links which are used to convey unconsumed water between the demand sites and waste water treatment plants to the supply chain. The transmission links are an integral part of the system since there are costs involved in their installation and maintenance which is an integral part of the system costs. Apart from the associated costs, the links also influence the overall flow of water in the system and the transmission of waste water out of the system.

1.6.3 Modeling process in WEAP

There are four main steps in the modeling process in the WEAP tool; these can be summarized as in the flow chart below:

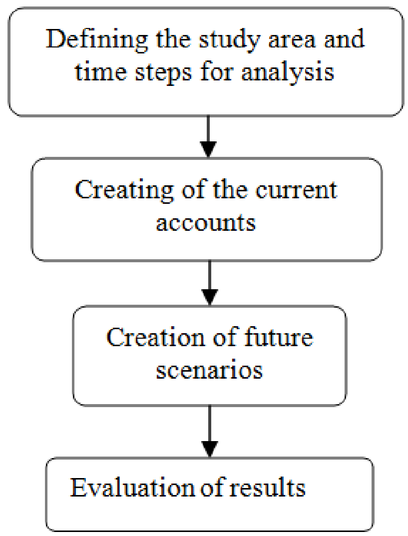


Figure 4: Key steps in the modeling process within WEAP tool

- Defining the area of study and the time steps for the analysis includes the design of the various water system elements and the definition of the analysis period. In defining the analysis period, the final year that should be considered in the scenario analysis and the minor time steps between each scenario are defined. These time steps are important since the system will only be able to produce results for the defined time steps. The user needs to define the start of a water year and whether the analysis should be carried out for every month for every month within a year and whether this should be repeated for the whole duration of the analysis.
- Creation of the current account; this involves creating an inventory of the current water demand and supply situation in the system under investigation. Specifically, the available water resources and the demand nodes are defined; additionally the inflows from different supply sources, the withdrawal conditions and recharge variable are also defined. This stage is critical for the success of the modeling exercise.

- Creation of future scenarios; scenarios are created based on key assumptions that are include in the system definition. The expected changes in the various indicators are factored in to the system as there can be used to address various “what if” questions as part of the scenario analysis.
- Once all the system parameters have been correctly defined, a click on the scenario explorer view will lead to a computation of results based on the set. The results which appear in both graphical and tabular formats results of which can be evaluated and the findings used in water planning to ensure that the future needs are met with the available water resources while maintaining the quality of water supplied to the users within the system and ensuring that the ecosystem integrity is also maintained.

1.6.4 Selected applications of WEAP tool

WEAP tool has been applied in various water related projects across the world. Some of the key areas of application have been in; modelling the effect of climate change on water resources and ecosystem services, water use planning, environmental planning, model building for hydrological engineering projects and water supply augmentation for various cities. In this study, we highlight some of the projects that have been carried out using the WEAP tool and these include:

- Water use and demand in Tana Basin: Analysis using the Water Evaluation and Planning tool (WEAP) (Hoff et al, 2007). This was a report that was compiled to bring together demand side issues, water supply, costs and benefits of green water management for the Upper Tana River basin in Kenya. Data on water demand from various users including irrigation farming, hydropower generation, and municipal water users were collected from various sources. Such data were then used to generate assumptions which were then implemented within WEAP tool to analyse about future water demand and supply trends in the basin; this was done as part of proof-of-concept report for the Green Water Credits project.

- Application of the Water Evaluation and Planning (WEAP) Model to assess future water demands and resources in the Olifants Catchment, South (Arranz and McCartney, 2007). In this study, WEAP model was applied to assess the impact of possible water demands in Olifants Catchment which is one of the 19 major catchments in South Africa. The analysis was carried out for a 30 year time period, with the base year as 1995 while the final year of analysis was 2025. The model results showed that different scenarios considered in the study would impact differently on the unmet water demand in the catchment. For instance, the establishment of an Environmental Reserve (an in-stream requirement to ensure the health of riverine ecosystems) would lead to shortages in the other sectors while a construction of more water storage infrastructure together with policy initiatives that encouraged water conservation resulted in reduction of unmet water demands.

- Modelling the impact of small reservoirs in the upper east region of Ghana (Hagan, 2007). In this thesis report, the student used WEAP model to assess the impact of upstream small scale reservoirs on downstream water users. Additionally, the model was also used to predict possible suitable reservoir sites that would ensure efficient and equitable use of the water resources in Upper Eastern Ghana.

- Application of Water Evaluation and Planning (WEAP): A model to assess future water demands in the Niger River (In Niger Republic) (Mounir et al, 2011). In the study, WEAP tool was used to assess the impact of population growth and climate change on demand for water resources in Niger River basin in the republic of Niger.

- Beyond building models: Using WEAP to inform climate change adaptation policy in Guatemala (Haris, 2007). In this study, WEAP analysis was used to project the impact of climate change on water resources as a precursor to understanding the kind of policy measures that needed to be put in place to reduce the country's (Guetamala) vulnerability in the event of the occurrence of the forecast climate changes.

1.7 Objectives of the study

The main objective of this study was to test and to demonstrate the suitability of WEAP as a tool for integrated water resource management. In particular, the exercise aimed at achieving the following specific objectives

i. To create a simple water management system using with various demand and supply nodes within the WEAP tool.
ii. To analyse the optimal use of water resources within the water management system as a result of changing demand and supply scenarios.
iii. To factor in the impact of population growth and changing climate scenarios water demand and supply equilibrium within a water management system.
iv. To examine how the system can be integrated with other existing GIS systems.

2.0 Methodology

2.1 Area of study

The Weaping River basin is used as the area of study in this exercise. This is a hypothetical data set associated with the WEAP system and is designed to aid the user in exploring various components of the WEAP system and to demonstrate some of the areas of application of the tool. The data is made up of a small water catchment with three rivers, two water reservoirs, two groundwater aquifers, two waste water treatment plants, one hydroelectric power generation station, and transmission links among other components of water management system.

2.2 Creating the water management system elements

In order to create a new water system, first and foremost GIS layers (vector files and topographic maps) were added and then used as geographic references for the various system elements. Within the schematic view, there are tools that can be used to add vector and raster layers and to specify the size of the water system under consideration. In the default data sets within the Weap river basin, county vector files and rivers were provided, these were used as references for various water system elements.

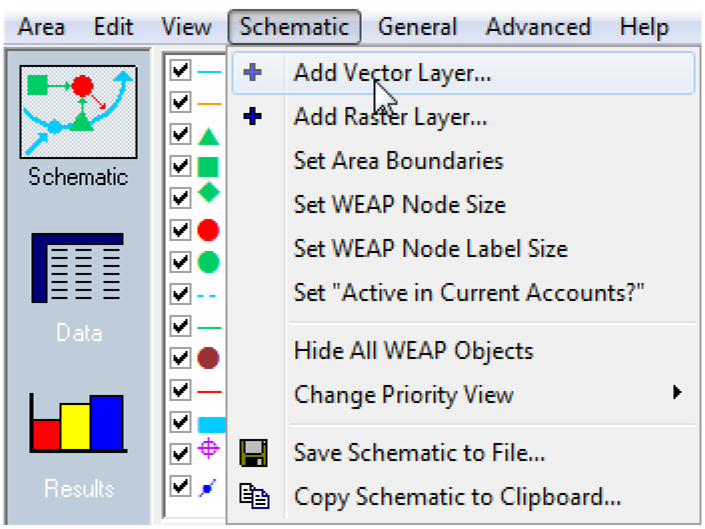


Figure 5: Procedure on how to add GIS layers onto WEAP tool

After adding the necessary GIS layers for instance, river networks, towns, catchments, topographic maps and plans showing water transmission lines and water treatment plants, the appropriate water element icons (figure 1) can be dragged and placed on the corresponding location within the water management system in the schematic view of the tool.

2.3 Defining the time steps

There are three options that are available for creating the time steps within the WEAP tool; (a) the time steps can be based on calendar years (b) all the time steps can be made equal for instance as monthly or annual time steps (c) the time steps can be entered manually, in this case the user explicitly specifies the time step which should be factored in the intermediate results from the system.

In this stage, there are two critical attributes of the water system that were defined. The first was the time horizon, that is, the current account year and the last year of scenarios; secondly the number of time steps per water year were defined. The second attribute in this stage is the water year start, indicating the particular month or date when the water year should start. Figure 6 shows screen short of how to define the parameters within the WEAP tool.

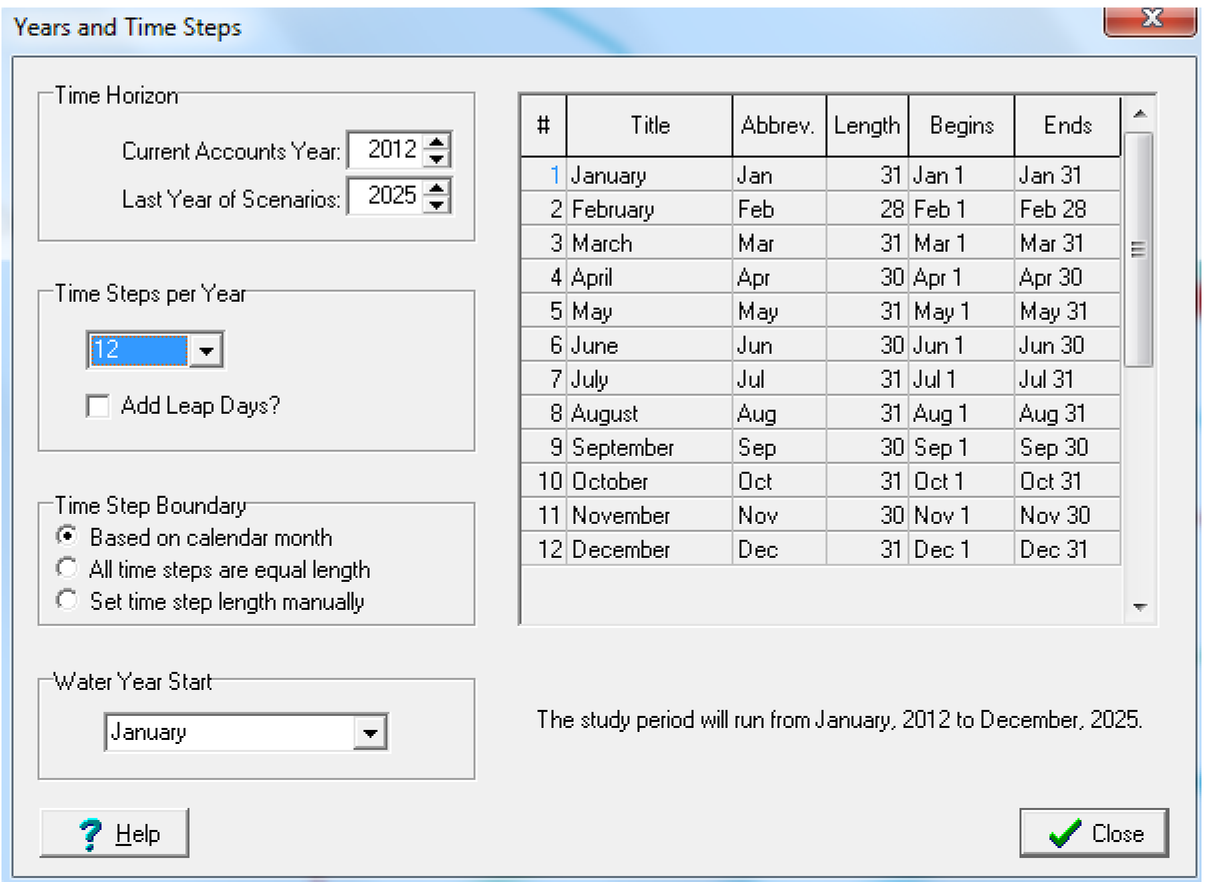


Figure 6: Defining time steps within WEAP

2.4 Creating the current accounts

The accuracy with which the current demand and supply of water resources in the area under consideration are defined has an implication on the accuracy of the results obtained from the analysis of various scenarios in the model.

The first step in this stage was to set the appropriate units that should be used to define the water demand, supply and costs associated with the various elements of the water system. Within the WEAP tool, there are predefined forms that allow users to set the units for the various elements of the water system including demand sites, rivers, reservoirs, ground water sources, other local supply, waste water treatment and the monetary units used in procuring various elements and for billing purposes. A click on either of these categories leads to a pop up window onto which the user can define and where necessary add the relevant units. For instance, figure 7 shows a demonstration on how the monetary units were defined and the conversion units with respect to the dollar.

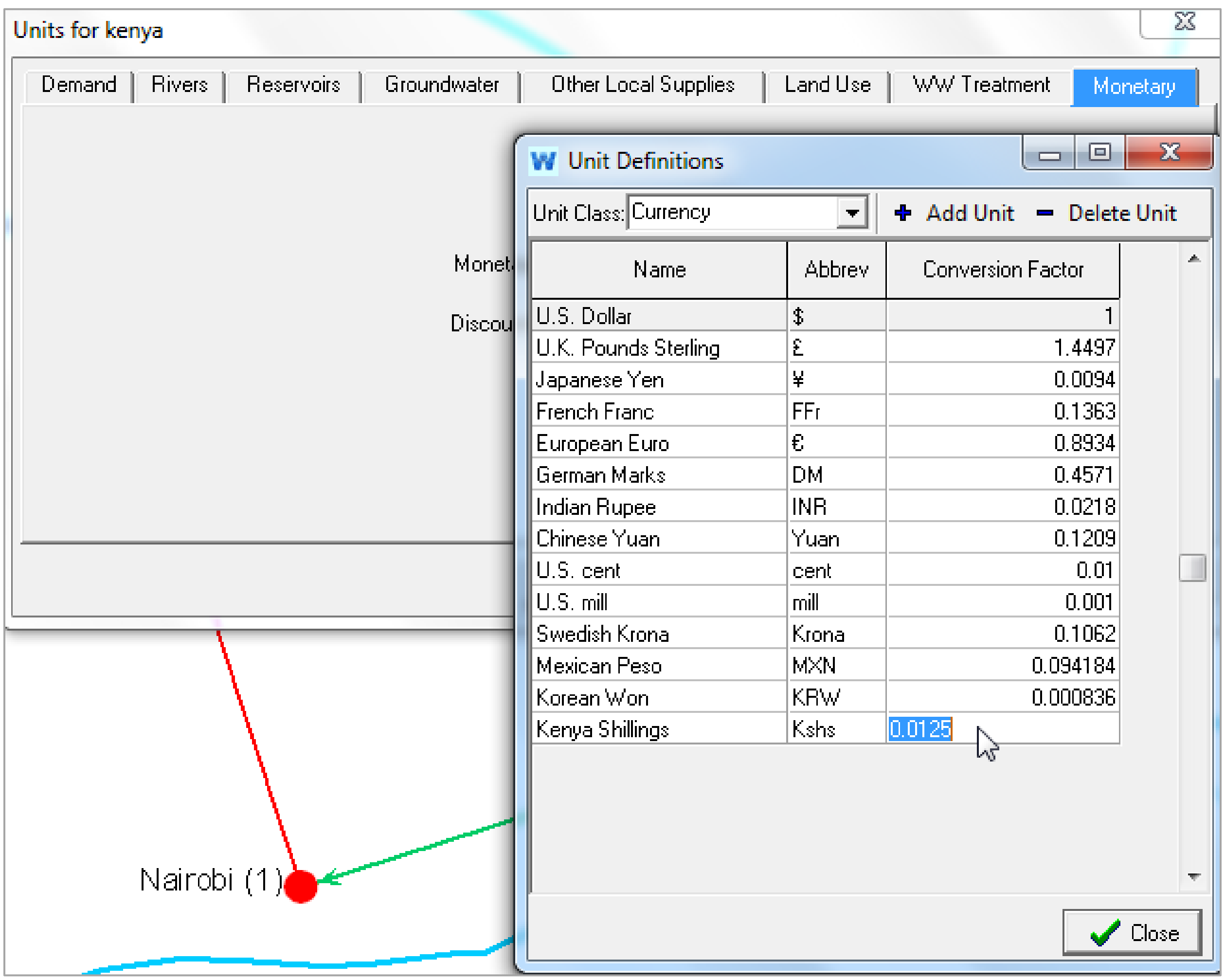


Figure 7: Setting up new accounts in WEAP

In the second step, the data view was used to populate the database of the various components of the water system under consideration. The key aspects that were defined in the data view were:

- **The key assumptions that have been factored into the system**, these were the expected changes in the various drivers and factors within the system that were critical in defining the various scenarios. For instance changes in GDP, changes in population, expected improvement in the water resource management and the impacts that such changes are likely to cause to the water supply or demand within the system under consideration. In this study only the changes in population were modified, otherwise for the other parameters, the default settings were used.

- **Demand sites within the system,** these are the various demand nodes within the system and are used to define the quantity (in volume) of water needs within the system. These nodes can have branches within them, for instance, when considering a city, branches can be created to represent industrial, domestic and agricultural water users and their water needs. The user can again go further and break the branches into smaller units, for instance within the domestic users, the particular needs can be specified for example showering, sanitation, washing, cooking etc. In the Weaping river basin, 4 demand sites were defined. These were South city, Industry North, Agriculture North and Agriculture West.

- **Hydrology:** The inflows to the model vary with time, WEAP tool offers two strategies on how to take into account such variations, in a situation where detailed historical information on inflows and forecasts about the future inflows into the system are available, these can be formatted and read into the model by using ReadFromFile function. The other method is the "Water Year Method" under which every year within the model distribution can either be defined as normal, wet, very wet, dry or very dry (Mounir et al, 2011). The inflows of the wet, very wet or dry and very dry years are defined relative to the inflows in a normal. Some information especially from historical inflows would be needed in order to define the average inflows in a normal year within the system. Once the normal year has been defined, the inflows in the other years are factored in as ratios of the normal year. For example, if a wet year averagely has 25% more inflow than a normal year then a value of 1.25 will be set to the wet year relative to the normal year.

- **Supply and resources**, these are either the supply nodes or the transmission links and the associated quantities, variations in quantities and the costs involved in running and maintaining them. The components in this class include rivers, groundwater aquifers, transmission links and return flow links. Within Weaping river basin, three rivers are considered Grey river, Blue river and Weaping river. Additionally the ground water sources are North aquifer and West aquifer.

- Water quality, water treatment plants and the associated costs of treatment are included. The maximum treatment capacity of each plant in terms of effluent flow is defined. When the maximum treatment capacity is defined, the implication is that any volume of effluents above the set threshold will not be processed. In Weaping river basin, two water treatment plants are included; these are South City WWTP and West WWTP.

After creating the components, the associated data can be entered manually, input from external data files including Microsoft Excel sheets or be generated from inbuilt expression builders and yearly time series wizards. Figure 8 shows a demonstration of how that data for the South City, which was one of the demand sites were defined. The city was mainly considered as a node for domestic water use, the users were categorised into two classes. These were the single family users and the multi-family users. It was further defined that the single family users constituted 42% of the population of the South city while the family users constituted 58% of the total population.

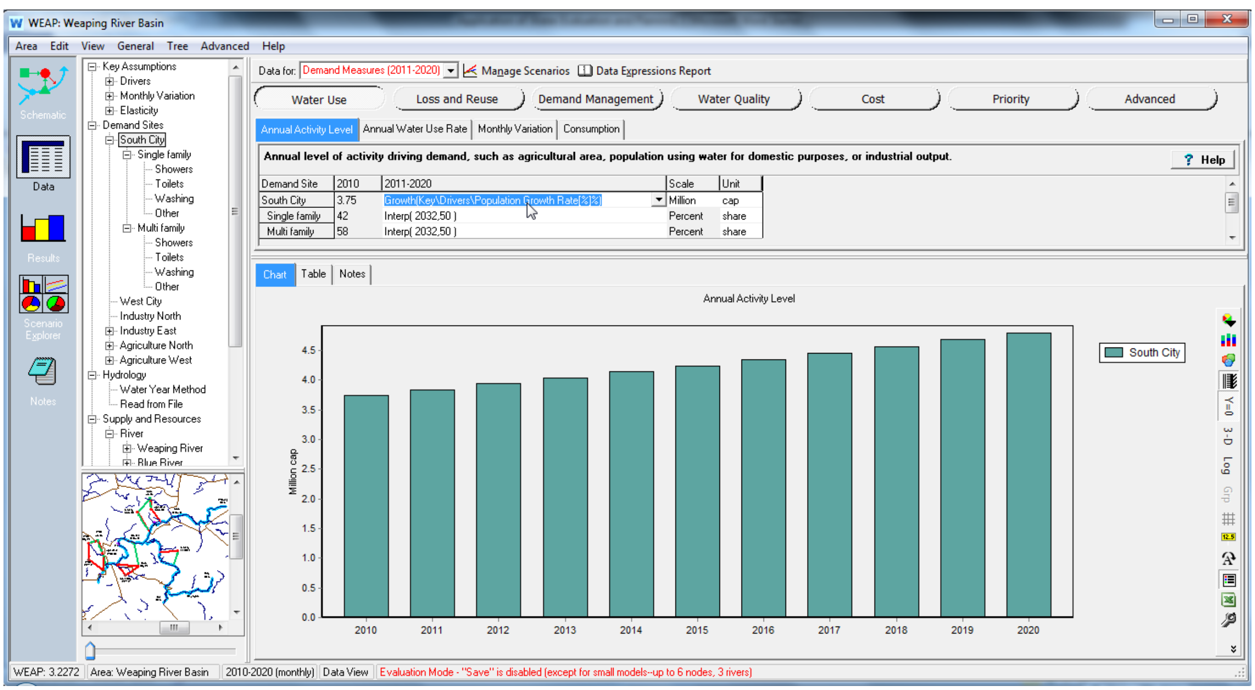


Figure 8: Data modeling within WEAP

2.5 Managing scenarios

As has been alluded to in the previous sections, the various scenarios in the model can be defined while setting the key assumptions for the data variables that are used in the model. The scenario explorer in the WEAP tool was used to either create new scenarios or to edit previously defined scenarios. Figure 9 shows the various options within the scenario explorer menu in WEAP tools.

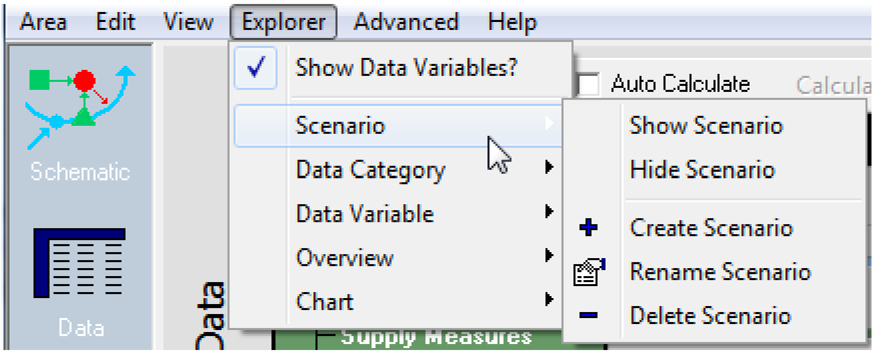


Figure 9: Defining future scenarios

In this study, two scenarios were defined, these were, (i) analysis of the impact of population growth on water resource demand, and (ii) analysis of the impact of climate change on water resource supply and demand.

2.5.1 Impact of population growth on water resource demand

In order to model the impact of population growth in the Weaping river basin, it was assumed that there would be an average population growth rate of 3.3% per annum for the entire duration of the analysis (2010-2020). The impact of change of population on demand for water was factored in to the data scenarios of the two cities in the basin; these were South City and the West City.

For the South city, the population in the year 2010 was 3.75 million people, with 42% of these living as single families while the remaining 52% lived as multi families. While for the West city, the population in 2010 was 2.025 million people all of whom are treated as a uniform entity.

Within the WEAP system, there are inbuilt mathematical functions which can be used to project time series interpolation of data. In this exercise, the linear interpolation function (Interp) was used. This is a function that allows for the calculation of a value in a given year by linear interpolation of time series of year pairs. The inputs in the formula include the current year, the year of interest, the current status of the variable to be interpolated (population in this case) and the rate of change in the variable. The implementation of the function for the South city was as follows; it is to be noted that since the interpolation is to be carried out for all the years of the analysis then they need not be defined, the system automatically recognizes that since the time steps had been defined.

Population in a given year = Interp (2010, 3.75, 3.3%)

This equation simply means that starting with a population of 3.75 million in the year 2010, the system should compute by linear interpolation the population of each year within the analysis period. Using the same logic, the population projection in the West city is computed using the formula

Population in a given year = Interp (2010, 2.025, 3.3%)

The results from these steps are assigned for the demand measures for the years (2011-2020). The resulting values can be viewed as charts, which can easily be exported to a Microsoft Excel spread sheet .In order to make the scenarios complete, is assumed that the changes in population do not have a direct influence on water supply, the supply measures are thus maintained as they were at the start year of the analysis.

2.5.2 Impact of climate change on water resources

The Water Year Method, which has already been described in this report, was used to analyse the impact of climate change on water inflows in each individual year within the analysis period. As had been stated earlier, the method allows the user to define five different wetness states, these are; normal, wet, very wet, dry and very dry.

The first step of implementing this method is to define, the relationship between the a normal year and the others states, in this study it was assumed that a wet year would have 25% more inflow than a normal year, while a very wet year would have 50% more inflow. Conversely, a dry year would have 25% less inflow while a very dry year would have 50% less inflow than a normal year. It is to be noted that the historical inflow data for the Weaping river basin was provided for the West aquifer and the Blue river, the data structure of these data is presented in Appendix 1

The second step was to define the inflow states that each of the years within the analysis period were likely to have. Normally, this should be inferred from climate prediction data, however since we did not have any future climate scenario data for the hypothetical basin under consideration, it was deliberately assumed that the inflows within the system would vary as indicated below:

Table 1: Implementation of the water year method

2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Normal	wet	very wet	wet	normal	dry	dry	very dry	very dry	dry	normal

These are implemented in the hydrology section within the data view of the system as shown in figure 10. According to the figure the different states, very dry, dry, normal, wet and very wet are represented on the vertical axis with values from 1 to 5 respectively. The horizontal axis shows all the years within the analysis period.

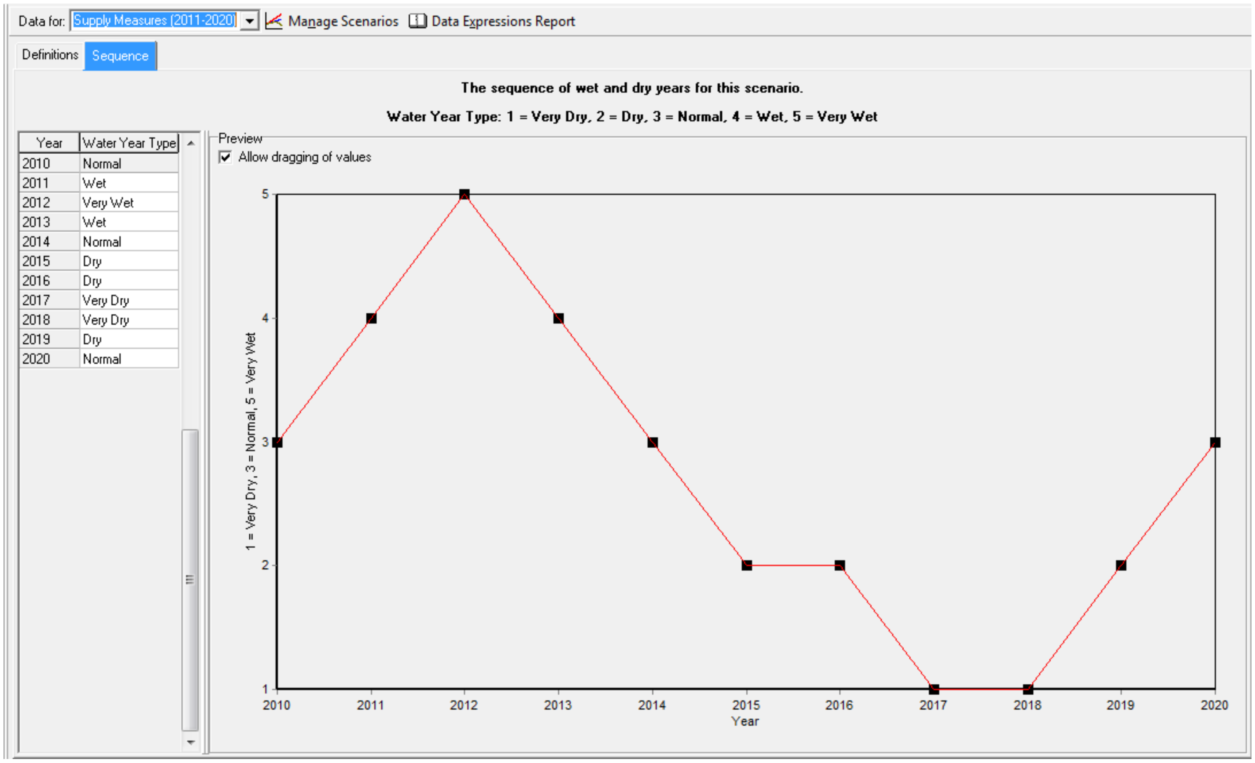


Figure 10: Defining the "Water Year Method" within WEAP

Once, all the scenarios were defined satisfactorily, the model was implemented and executed by simply clicking on the scenario explorer icon, in order to view the latest results as per the defined parameters, an option was selected within the model GUI that allowed the model to compute scenarios by using the updated information. With the updated information, the system then computed the demand and supply relationships of the various model elements for the whole duration of the analysis period. This process was largely internal and the user is not in control of the internal workings of the system. The results were computed for all the defined time steps (for each month) within the analysis period. Once the processing was completed, a graphical representation of the data used in the modelling and the results for different supply and demand elements were shown on the scenario window. The figure 11 is a graphical representation of the results from the analysis. Some of the results shown graphically were a representation of supply requirements, reservoir storage volumes, unmet demands, groundwater storage and the water demands.

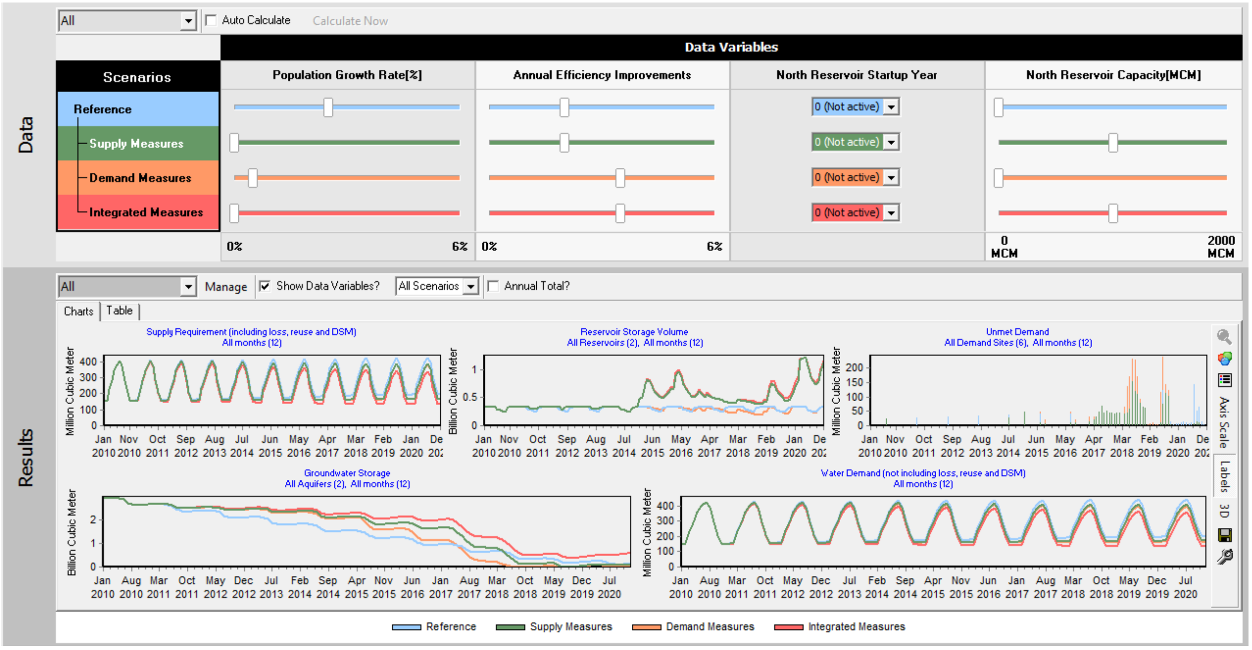
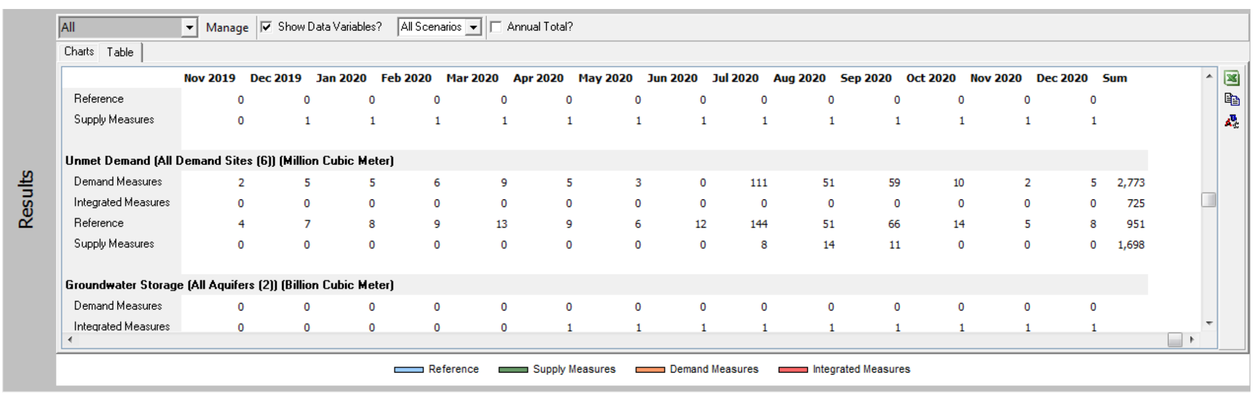


Figure 11: Graphical representation of results in the scenario view

The result can also be viewed in tabular format for each of the time steps within the analysis period; it is also possible to export the tabular results to Microsoft Excel files



	Nov 2019	Dec 2019	Jan 2020	Feb 2020	Mar 2020	Apr 2020	May 2020	Jun 2020	Jul 2020	Aug 2020	Sep 2020	Oct 2020	Nov 2020	Dec 2020	Sum
Reference	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Supply Measures	0	1	1	1	1	1	1	1	1	1	1	1	1	1	
Unmet Demand (All Demand Sites (6)) (Million Cubic Meter)															
Demand Measures	2	5	5	6	9	5	3	0	111	51	59	10	2	5	2,773
Integrated Measures	0	0	0	0	0	0	0	0	0	0	0	0	0	0	725
Reference	4	7	8	9	13	9	6	12	144	51	66	14	5	8	951
Supply Measures	0	0	0	0	0	0	0	0	8	14	11	0	0	0	1,698
Groundwater Storage (All Aquifers (2)) (Billion Cubic Meter)															
Demand Measures	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Integrated Measures	0	0	0	0	0	1	1	1	1	1	1	1	1	1	

Figure 12: Tabular data from modeling

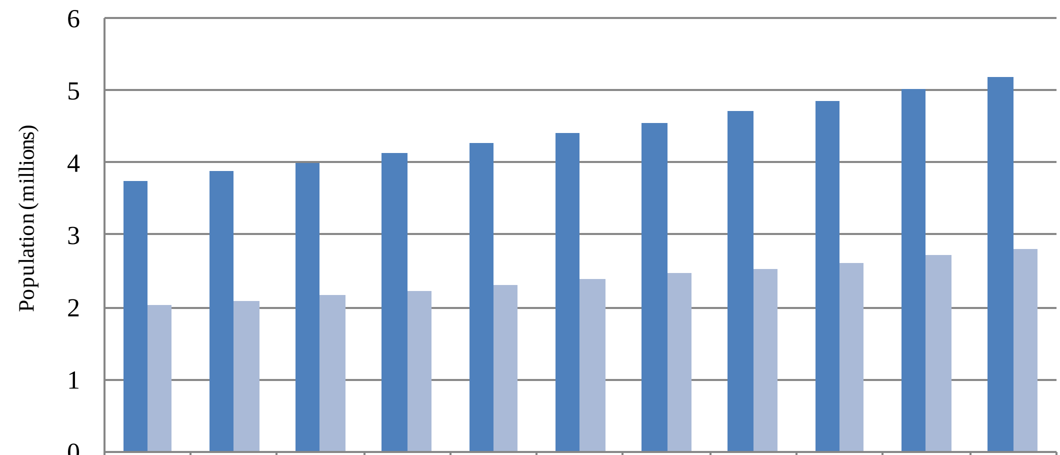
In summary, the resulting charts and associated tables give an indication of how the supply and demand situation of the water management system under consideration is likely to be while taking into account the influence of the defined scenarios.

The results are given for all the nodes (both supply and demand sites) in the system and in all the time steps; it is upon the user to “zoom in” to the detail of interest. For instance if the user is interested in the unmet demand in a particular demand site in a given year, then they can select the chart for the unmet demand and within the chart, select the site for which analysis should be shown and the duration of interest. The WEAP tool also has different menus that can be used to define how the graphs should be portrayed. It is possible to have different types of maps including bar, line, step, column, pie and area types. Additionally the graphs can be stacked together and represented in three dimensions.

Apart from the nature of the graphs, different elements to be included the graphs for instance the title, legends, borders, palettes and attributes to show can also be edited.

3.0 Results and discussions

From the linear interpolation of the population data in both South city and West city, the projected values were exported in Microsoft Excel file format and used to plot the chart as shown in figure 13. The figure is a representation of the values obtained from the interp( ) function within the WEAP tool.



	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
South City	3.75	3.8738	4.0016	4.1336	4.27	4.411	4.5565	4.7069	4.8622	5.0227	5.1884
West City	2.025	2.0918	2.1609	2.2322	2.3058	2.3819	2.4605	2.5417	2.6256	2.7122	2.8017

Figure 13: Population projection in South City and West City

3.1 Unmet demand

Since the main focus of the scenarios in this study were to assess the impact of population growth and climate change on water demand and supply equilibrium, our main focus of interpretation was the unmet demand resulting from the defined scenarios. Figure 14 shows the chart for the unmet demand in all 6 demand sites in the system and in all the time steps (months) considered in the analysis period. By unmet demand, we refer to the scenarios where the total water demand is the system would be higher than the total water supply (inflows) into the system based on the parametization of the system. The graph is therefore a representation of the demand relative to the supply in that particular time step, as such the time steps where the supply is considered to be higher than the demand are actually considered to have a zero unmet demand.

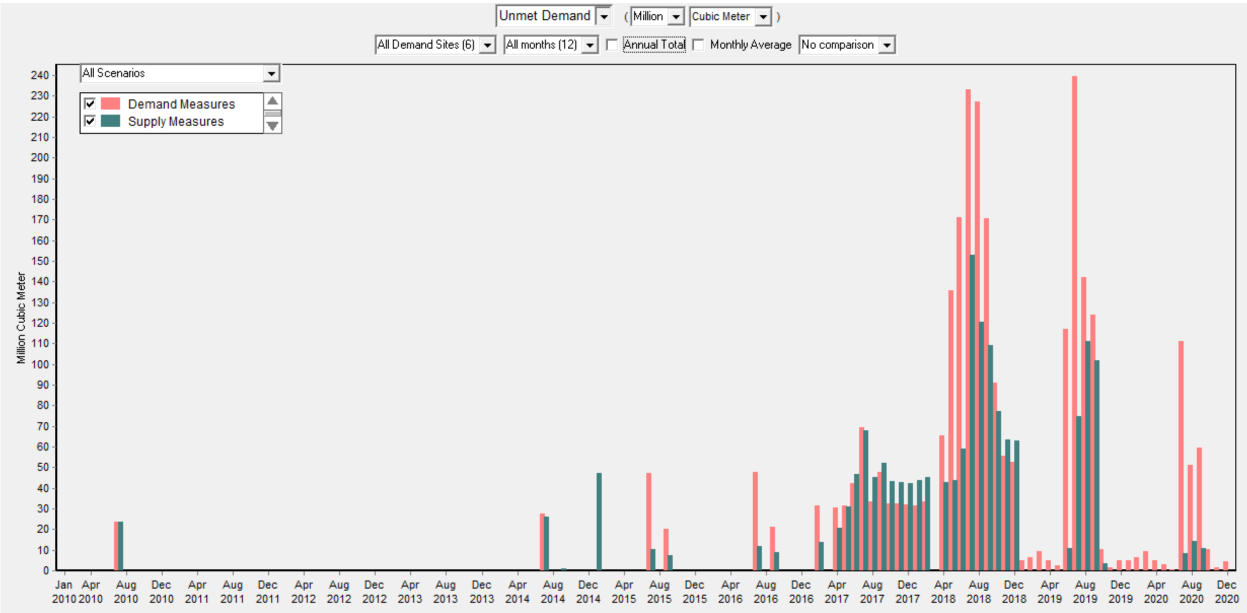


Figure 14: Unmet demand within the system

From the chart, it is evident that the if the current supply is maintained as it is, then by considering the scenarios that were set, the water demand will be higher than the water supply beginning from around the year 2015 and reaching critical levels from the year 2018 onwards. The results in figure 13 are sensible when considered with respect to the parameters set in the "water year method" in figure 9. In figure 9, the year 2014 is a "dry year" and it gets worse to a series "very dry" years until the year 2018 when the inflows increase in the system, this can explain the onset of unmet demand in the year 2014.It is also possible to "zoom in" to a particular demand sites and visualize the relations between demand and supply balance given the influence of the defined scenarios. Figure 14 shows the unmet demands in South City demand site.

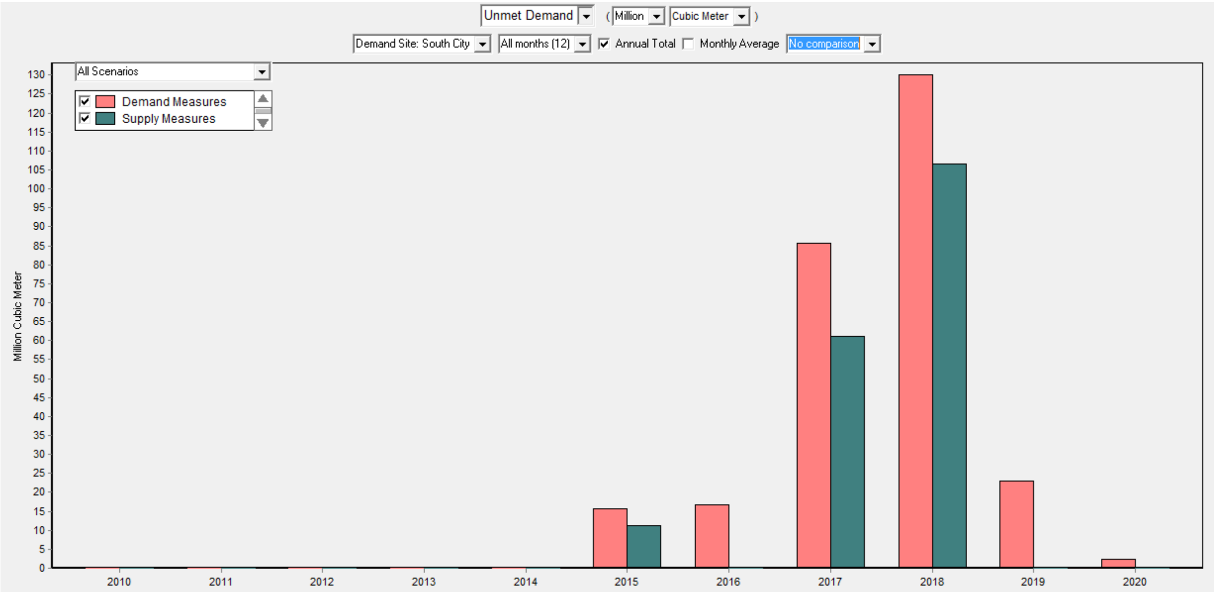


Figure 15: Unmet demands in South City demand site.

The figure 15 shows the unmet annual water demand (demand and supply balance) in South City site in the analysis period. In this case, the results were filtered out to show only the annual total unmet demand and where there is unmet demand the respective supply volumes are also shown. Again it is evident that from the year 2014 with all the parameters remaining as set there is likely to be an onset of unmet demands.

Further still, a comparison against the supply measures were also displayed so as to give an indication of the actually volume of unmet demand, this is demonstrated in figure 15. From the figure, we can see the onset of the unmet demand will be 2014 and that the peak will be in the year 2017 at a value of 23 million cubic meters, thus apart from just showing the onset, the model also gives an indication of the amount thus making it more useful to policy makers.

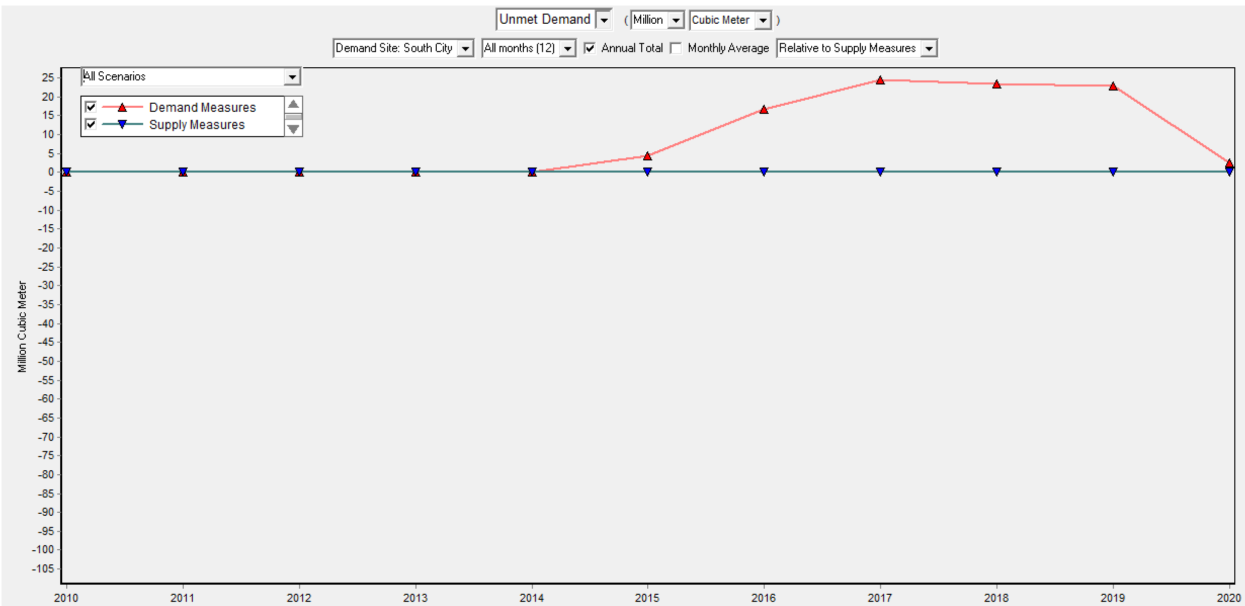


Figure 16: Predicted amount of unmet water demand in South city

This procedure can be repeated in all the demand sites under analysis to determine the onset of unmet demand for each demand sites and the associated amount of the unmet demand in each site.

3.2 Ground water storage

Apart from the results of unmet demand in each demand site, the scenario explorer can also be used to visualize the changes on the supply elements of the system under consideration. For instance it is possible to assess and to interpret the changes in the ground water aquifers (North and West aquifers were used in this study respectively) as demonstrated in the figures 17 and 18. In order to be able to visualize the changes in the ground water storage within a water management system, some key parameters should be set about ground water storage sites when setting up the model parameters. Key among the parameters of the ground storage that should be defined and that were indeed defined in this study included; the storage capacity of the ground water storage, the initial storage in the start year, the maximum withdrawal and the rate of natural recharge. For instance, the north aquifer was set to have a storage capacity of 2500 million cubic meters, the initial storage was 900 million cubic meters, and the maximum withdrawal allowed was 100 million cubic meters per month while the natural recharge was set at 200 million cubic meters per annum. The aquifer is linked to two demand sites, industrial north and agriculture north. As a result of these settings and the changing inflow scenarios incorporated in the model, the supply and demand on the aquifer varies as indicated in figure 16. The figure actually showing that with settings staying as originally set, then there would be instances when the demand measures would be high than the supply measures.

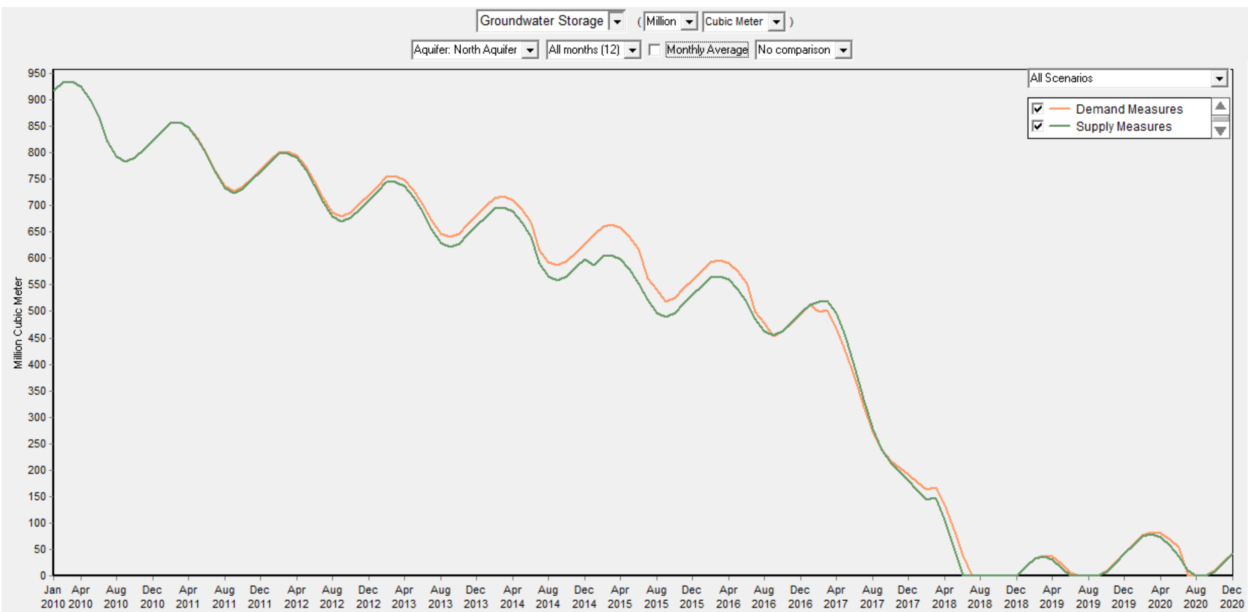


Figure 17: Changes in water demand and supply measures in northern aquifer

In the second aquifer, the west aquifer, the storage capacity of the aquifer was set at 2500 million cubic meters, the initial storage at 2000 million cubic meters, the monthly maximum withdrawal at 200 million cubic meters, and the annual natural recharge at 450 million cubic meters. The aquifer was linked to the West city and Agriculture west demand sites. Once again with the settings into the node, the water demand and supply vary as indicated in figure 17. Because of the relatively higher volume of initial storage, the water supply reduces in the aquifer however the supply still remains higher than the demand. it is to be noted that the graph of the demand measure does not represent the actual demand but rather the amount of demand relative to the water supply from the aquifer.

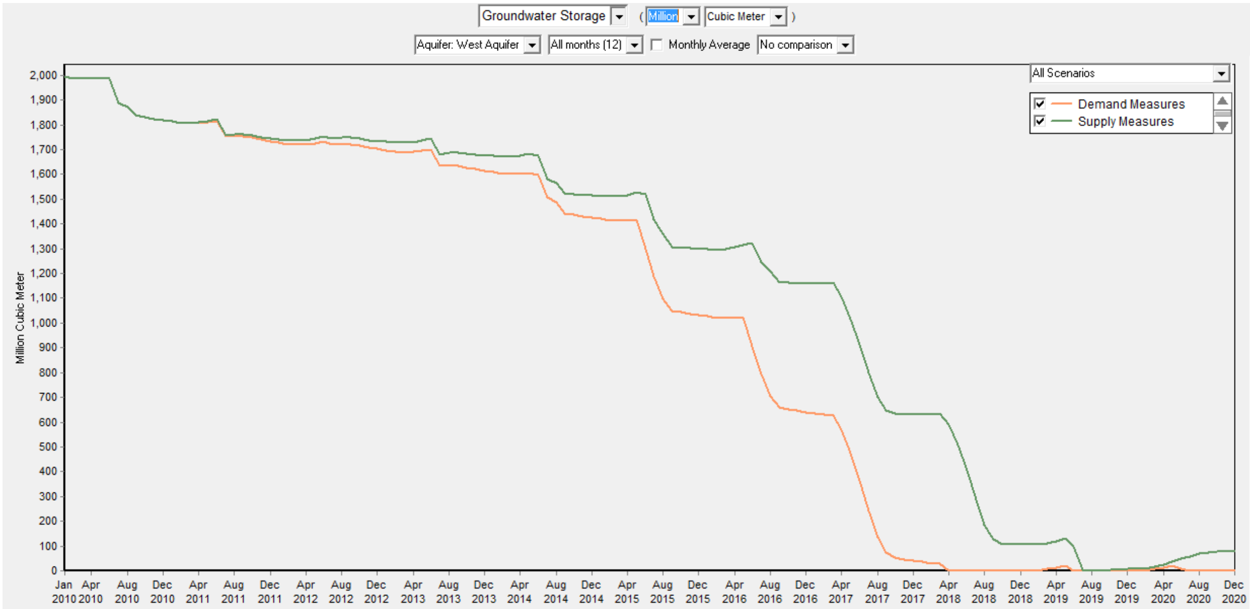


Figure 18: Changes in water supply and demand measures in West aquifer

Depending on the purpose and nature of the analysis all the resulting charts resulting from the defined scenarios can be interpreted and used to make policy and water resource management decisions.

Finally, it is possible to visualize the water management system under consideration on Google Earth platform by saving the schematic view in Google Earth kmz file format. Therefore the tool makes it possible not only to present the results not only in graphical and tabular formats, but also with a sketch of the overall system outlook of the system under consideration. The schematic map of the water management system under consideration in this study is shown in figure 18.

Additionally, apart from the results and the schematic sketch, a detailed report on all the data input into the system and the main assumptions can be generated automatically from the tool and shared with various stakeholders for ease of referencing.

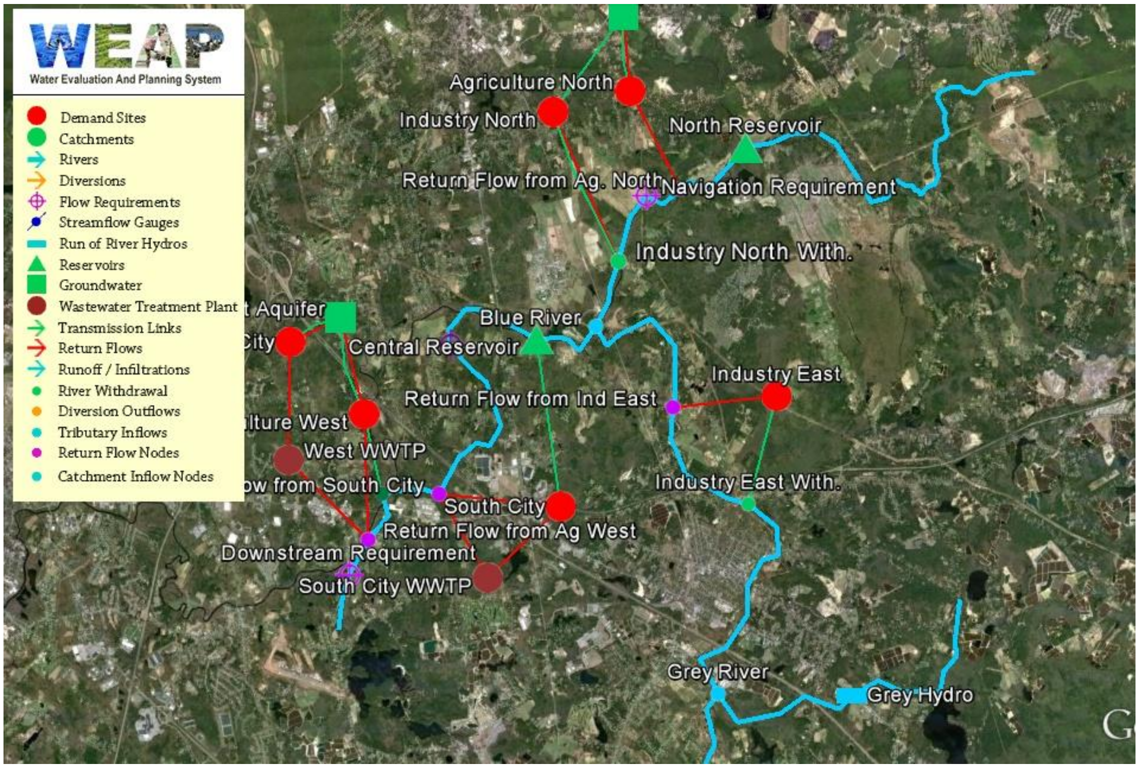


Figure 19: Schematic view of Weaping river basin

4.0 Conclusion

From the study, we confirmed that WEAP system is indeed a valuable tool for water resource planning and management. It is easy to learn and use and applicable in a variety of settings (depending on the licence). The tool implements a detailed analysis and equally outputs detailed result for virtually all the critical components of the water ecosystem under evaluation. The power of the tool lies in the fact that data can be entered from various sources including text files, spread sheets, and by using the various in-built tools and functions within the system itself. Additionally, the tool is also capable of implementing a variety of scenario analysis and this is possible within a short time.

Secondly, it is possible to input GIS layers mainly for visualization purposes. GIS shapefiles and raster files can be loaded onto the schematic view of the WEAP tool and used to georeference various system components. The designed schematic view can also be viewed on Google Earth platform by simply saving it in Google Earth file format. The schematic view is important as it gives a visual view of the overall outlook of the system. By using the schematic view, the policy makers are able to visualize the linkages between the different nodes in the system. As such the system does not only result in figures on quantities and costs in water demand and supply, but it also offers stakeholders with an opportunity to link the figures to particular geographic locations within the system.

In the process of exploring the tool, it was noted that in order to have credible results from the analysis, it is important to have a variety of detailed data on the system under consideration. Such data may include demographic data, stream flow data, monthly water use information for every demand site, reservoir and aquifer capacities, water system management and running costs, climate data among others. These data are critical and may actually be a deciding factor on whether to use the tool as the reliability of the resulting scenario analysis rely heavily on the quality of the input data and the veracity of the assumptions factored into the model.

Having successfully edited the tutorial data and implemented two scenarios, which were the impact of population growth and climate change into the system, it is our conviction that the objectives set out for this exercise were affirmed. We however acknowledge that since we were using a trial version and not a licensed version of the tool, our study did not extensively capture the full strengths and capabilities of the WEAP tool especially the ability to integrate it with other user-developed scripts. Similarly, since we lacked the necessary data, we were not able to test the inbuilt models within the tool like MODFLOW (for groundwater flow modelling) and MODPATH (for groundwater particle tracking). These are possible areas of consideration in future studies.

As we used the tool, we noticed that the integration of the tool with other GIS is not very strong since it only allows the use to add and visualize GIS data while not allowing any extensive analysis of such data. Strengthening the integration of the tool with GIS will surely make it an even stronger tool as most water related problems have spatial characteristics which can be understood by incorporating such spatial characteristics into the tool. Additionally it was noted that the tools is a kind of a "black box" model since the user is aware of the input but is not has very limited knowledge on the internal workings of the system.

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Appendix 1: Data structure of historical inflow data

Unit = Cubic Meters per Second (cms)

FirstYear = 1950

[GROUNDWATER]

"West Aquifer"

1950, 8.606448, 7.03752, 21.57701, 15.24466, 11.19773, 8.040048, 5.417616, 3.573984, 3.967632, 4.0356, 3.942144, 3.302112
1951, 2.659248, 7.360368, 4.820064, 4.907856, 4.449072, 5.782944, 2.851824, 2.118336, 2.698896, 2.155152, 2.330736, 4.77192
1952, 11.20906, 14.1515, 8.38272, 7.24992, 5.695152, 4.542528, 3.80904, 4.568016, 3.154848, 4.406592, 4.766256, 11.22038
1953, 7.921104, 11.92838, 10.63699, 15.64114, 11.09861, 7.510464, 5.120256, 3.508848, 4.086576, 3.831696, 6.020832, 13.91928
1954, 9.116208, 11.15242, 10.50389, 12.24274, 15.61565, 7.949424, 10.0621, 8.614944, 4.398096, 4.09224, 4.165872, 5.22504
1955, 4.684128, 9.413568, 5.468592, 5.171232, 4.774752, 3.474864, 5.117424, 5.556384, 3.276624, 3.163344, 5.440272, 5.32416
1956, 3.981792, 3.86568, 4.664304, 3.338928, 2.94528, 2.061696, 1.509456, 1.6284, 2.475168, 5.038128, 6.369168, 8.546976
1957, 8.173152, 9.484368, 11.54606, 9.16152, 6.162432, 5.094768, 3.973296, 3.081216, 2.659248, 1.849296, 2.693232, 4.004448
1958, 7.402848, 5.151408, 4.075248, 6.5136, 3.375744, 2.310912, 2.693232, 2.104176, 2.738544, 3.2568, 3.163344, 2.832
1959, 5.669664, 5.641344, 8.532816, 6.666528, 5.995344, 11.38464, 10.57752, 6.465456, 6.720336, 11.69899, 6.550416, 7.836144

[HEADFLOW]

"Blue River"

1950, 17.22706, 10.33397, 41.10081, 21.54869, 12.6647, 5.882064, 2.271264, 2.483664, 11.49226, 3.792048, 3.528672, 3.22848
1951, 2.982096, 17.88408, 8.844336, 8.97744, 11.59704, 5.96136, 2.630928, 2.829168, 2.325072, 1.21776, 1.860624, 6.125616
1952, 16.66632, 38.58034, 11.5489, 20.58581, 8.654592, 6.380496, 6.21624, 3.27096, 10.63416, 6.029328, 6.675024, 22.04995
1953, 13.7437, 20.48669, 19.41619, 22.55688, 14.83685, 6.728832, 3.395568, 3.953472, 11.72165, 2.7612, 12.14928, 33.88488
1954, 15.88469, 15.91584, 17.83027, 21.05592, 26.78789, 6.830784, 13.14898, 3.746736, 15.67512, 2.738544, 4.51704, 7.252752
1955, 6.68352, 21.81206, 7.921104, 6.989376, 12.35602, 8.801856, 7.346208, 3.489024, 8.125008, 4.222512, 5.386464, 9.031248
1956, 5.06928, 6.105792, 8.207136, 3.687264, 2.80368, 1.874784, .447456, 2.240112, 4.157376, 4.103568, 5.828256, 8.051376
1957, 20.75856, 10.43592, 16.96085, 7.417008, 4.916352, 8.379888, 5.89056, 1.418832, 8.11368, 1.135632, 3.273792, 4.505712
1958, 10.50955, 9.184176, 4.910688, 7.266912, 2.478, .586224, 1.26024, 1.880448, 3.995952, 3.967632, 3.59664, 2.560128
1959, 5.740464, 6.842112, 11.5489, 10.00546, 7.84464, 15.85637, 20.35642, 7.417008, 8.544144, 24.12864, 9.43056, 12.37584

[REACH]

"Blue River","Below Industry East With."

1950, 3.205824, 1.948416, 7.765344, 3.52584, 2.94528, 1.314048, .504096, .515424, 2.016384, .767472, .705168, .620208
1951, .555072, 3.188832, 1.523616, 1.432992, 1.72752, .90624, .458784, .487104, .563568, .271872, .365328, 1.229088
1952, 2.928288, 6.366336, 1.945584, 3.6816, 1.427328, 1.311216, 1.608576, .654192, 1.77, 1.328208, 1.127136, 3.664608
1953, 2.319408, 3.460704, 3.726912, 3.90816, 2.325072, 1.229088, .659856, .674016, 2.225952, .586224, 2.480832, 6.493776
1954, 2.829168, 3.007584, 3.29928, 3.616464, 4.61616, 1.149792, 2.693232, 1.127136, 2.359056, .716496, 1.002528, 1.57176
1955, 1.365024, 3.234144, 1.416, 1.268736, 1.248912, .727824, 2.645088, 2.231616, .8496, 1.059168, 1.483968, 1.67088
1956, 1.050672, 1.084656, 1.6992, .996864, .674016, .2832, .118944, .118944, .529584, 1.733184, 2.749872, 2.248608
1957, 3.404064, 2.741376, 3.474864, 1.753008, .900576, .781632, .461616, .209568, .175584, .150096, .413472, .674016
1958, 1.951248, 2.118336, .982704, 1.707696, .577728, .175584, .121776, .320016, 1.087488, .897744, .770304, .75048
1959, 1.07616, 1.333872, 1.710528, 1.707696, 1.23192, 2.795184, 3.692928, 1.180944, 2.299584, 3.85152, 2.427024, 2.509152

[RESERVOIR]

; No local reservoirs exist

[OTHER]

; No other local supplies exist