Documentation and Testing of the Aragvi River Basin Planning Model

and

Evaluation of Water Management Strategies

by

Samuel Sandoval Solis, Ph.D.
J. Pablo Ortiz Partida
Peter Hartsough, Ph.D.
Lindsay L. Floyd

And

Kakha Bakhtadze,
Nino Kheladze,
Lasha Sukhishvili, Ph.D.
Eliso Barnovi
Irakli Kobulia

July 2017

WATER MANAGEMENT LAB

University of California, Davis
1 Shields Ave. Dept. LAWR, Bldg. PES 1110, Davis, CA, 95616
This document is available online via World Wide Web at
http://watermanagement.ucdavis.edu/e-library/

Acknowledgments

This work completes part of a project with USAID.

ABSTRACT

The Aragvi River Basin, located in the North East part of Georgia, belongs to the Mtkvari (Kura) River Basin. Administratively, the basin is located in the Mtskheta-Mtianeti region and is split between the Kazbegi (Origin of the river), Dusheti and Mtskheta (confluence to Mtkvari) municipalities. Tbilisi, the capital of Georgia, relies on water from this basin, but there are other water uses such as hydropower generation and irrigation drawing from the same water source. Throughout the last few decades, there has been a competition for water, and with a growing population this competition is expected to increase in the near future.

The USAID – G4G is a five-year USAID funded project implemented by Deloitte Consulting LLP since 2014. G4G is designed to enhance governance in selected business enabling areas. Water resource management, one of the main components of the project, aims to support the Government of Georgia (GoG) to improve water resource management across multiple competing interests. An important water resource management activity for Georgia is the balancing of the needs between competing users and consumers of water. Under the Water Resource Management Component, G4G will build counterpart capabilities in developing computer models for water resource management policy and planning. Specific objectives of the grant - "Piloting water allocation modeling using WEAP in the Aragvi River Basin" are to: (1) develop a water allocation model and evaluate current and alternative water management strategies (called scenarios) for the Aragvi River Basin in WEAP; (2) interact and coordinate with the MoENRP and other stakeholders to ensure agreement on model scenarios; (3) Build capacity within GoG in WEAP modeling. This report falls under this collaborative project by documenting and testing the planning model of the Aragvi Basin constructed using the Water Evaluation and Planning system (WEAP) platform.

The documentation of the model addresses the inputs for demands and supplies for the Aragvi River Basin. The model is also set up to include the water allocation policy for different user according to the Georgian Water legislation and the operating policies for Jinvali reservoir. For the water inflows to Jinvali reservoir, two time series were estimated: (1) a less water abundant monthly time series, from 1960 to 1992, estimated using four streamflow gage stations upstream of Jinvali reservoir, and (2) a corrected monthly time series, from 1987 to 2016, estimated using inflow data provided by the Georgian Water and Power (GWP), company that operates Jinvali reservoir.

This report also describes the verification process of the model to make sure that it is representing as accurately as possible the water supply and water demand system of the Aragvi River Basin. This verification demonstrated that the model is simulating adequately the water allocation systems and Jinvali reservoir operation policy.

TABLE OF CONTENTS

INDEX OF FIGURES

INDEX OF TABLES

1. INTRODUCTION

The Aragvi River basin (Figure 1) is located in the North-East of Georgia on the southern slopes of the Main Caucasus Range. The river length is 112 kilometers, and the catchment area of the basin is 2,724 km^2. The basin of the Aragvi River, a sub basin of the Mtkvari River system, administratively is located in Mtskheta-Mtianeti region (Kazbegi, Dusheti and Mtskheta municipalities).

The Aragvi River is part of a river system integrated by the following main rivers: Mtiuleti (White) Aragvi (41 km), Gudamakari (Black) Aragvi (30 km), Khevsureti Aragvi and Pshavis Aragvi (56 km). The Aragvi River is a main part of this river system and originates in the Northeastern part of the volcanic mountain referred as Keli. In the upper and middle sections, the Aragvi River is a typical mountain river, but in the lower part it flows in Mukhran-Saguramo valley and has features resembling a river valley. Near the city of Mtsketa, Aragvi River flows into River Mtkvari (Kura).

Jinvali reservoir, which is an artificial reservoir, divides the basin into an upper and a lower section, modifying the hydrologic regime of the river. The majority of water resource consumers are located in downstream of Jinvali reservoir, in the lower reaches of Aragvi River. water from Aragvi River is used for irrigation, water supply to the city of Tbilisi and is the main source of water for local settlements and small manufactures.

Another important feature of the Aragvi River Basin is the Zhinvali hydropower dam. The Zhinvali hydropower dam is one of the largest dams of Georgia, is 102-meters high and generates 130 MW hydro-electric power. It was constructed in 1986 and forms the Jinvali Reservoir.

Figure 1 Aragvi River Basin

1.1. USAID – G4G Project Description

The construction of the Aragvi River Basin Planning model was conducted in conjunction with the Environment and Development (ED) and USADI-G4G partners in an attempt to promote regional cooperation between multiple institutions that administer, operate, allocate and regulate water resources in Georgia. **The overall objective of this project is to build a planning model to evaluate current and alternative water management strategies in the Aragvi River Basin**. The planning model was built using the Water Evaluation and Planning (WEAP) platform.

This report focuses on the construction of the Aragvi River Basin planning model and the result obtained from modeling exercise related to current and alternative water management strategies. For the construction of the Aragvi River basin model, this report documents data inputs into the model, verification, and testing of the model.

1.2. WEAP Software

The software used for modeling the water management system of the Aragvi River Basin is Water Evaluation and Planning System (WEAP) developed by the Stockholm Environment Institute (Yates et al., 2005). The license fee for this software is waived for academic, governmental, and other non-profit organizations in developing countries, including Georgia. Some of the highlights for using this software are that it has an integrated approach, easily involves stakeholders, uses a priority-drive water balance methodology, and has ways to implement different scenarios in a friendly interface (Table 1). WEAP software also uses a graphic user interface that imports graphic files from other software systems to help create models, such as geographic information systems (GIS) Shapefiles. The WEAP model schematic generated for the Aragvi River Basin is shown in Figure 2. This team has developed WEAP tutorials in Georgian and English for the Aragvi River Basin. These exercises are easy to use, and provide systematic instructions on how to start the construction of a WEAP model for this particular basin.

Table 1 WEAP Software Highlights (WEAP 2017)

Integrated Approach	Unique approach for conducting integrated water resources planning assessments
Stakeholder Process	Transparent structure facilitates engagement of diverse stakeholders in an open process
Water Balance	A database maintains water demand and supply information to drive mass balance model on a link-node architecture
Simulation Based	Calculates water demand, supply, runoff, infiltration, crop requirements, flows, and storage, and pollution generation, treatment, discharge and in stream water quality under varying hydrologic and policy scenarios
Policy Scenarios	Evaluates a full range of water development and management options, and takes account of multiple and competing uses of water systems
User-friendly Interface	Graphical drag-and-drop GIS-based interface with flexible model output as maps, charts and tables

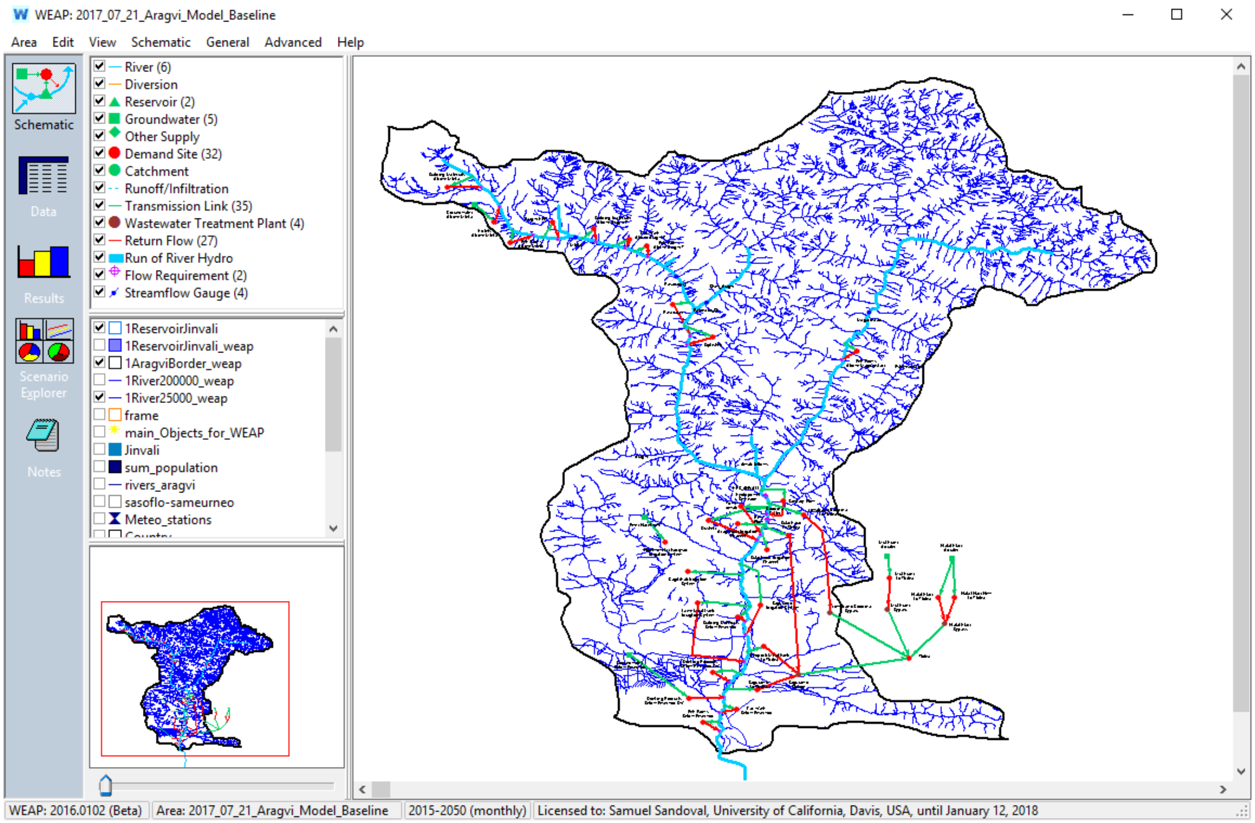


Figure 2 Schematic of the Aragvi River Basin Planning Model.

The Aragvi River Basin planning model (from now on referred as *Aragvi model*) utilizes three main screens. The first screen is the Schematic View (Figure 2). This screen enables the User to add nodes, demand sites, transmission links, etc. The second screen is the Data View (Figure 3 left). There are six main branches to the Data View including Key Assumptions, Demand Sites, Hydrology, Supply and Resources, Water Quality and Other Assumptions. The project is currently working with four of the six branches, Key Assumptions, Demand Sites, Supply and Resources and Water Quality. Each of these areas is further broken down into smaller branches. First, the branches for Key Assumptions are currently being used for, water demands, reservoir operation policies, and priority levels (Figure 3 right). Second, every Demand Site has its own branch (Figure 4). Lastly, Supply and Resources is divided into four sub-branches, River, Groundwater, Transmission Links, and Return Flows (Figure 5). The last screen view used is for results. This screen is used after the model has been run and displays the results graphically or in tabular format. The model also has a feature where the user can export the results to a comma separated variable (.csv) file or a spreadsheet file.

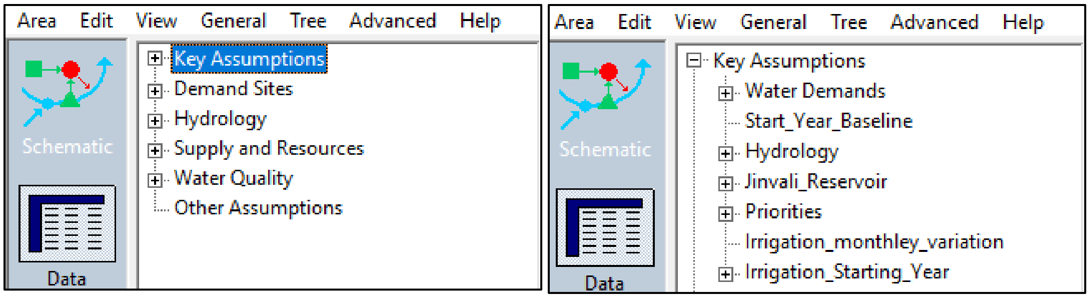


Figure 3 Left Data View for WEAP and right: Key Assumptions Branches

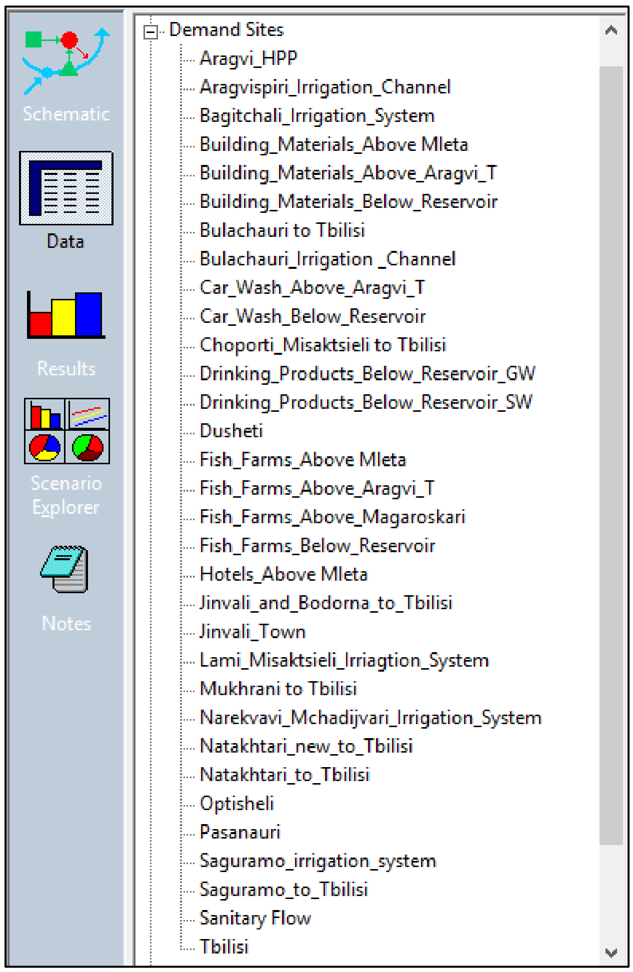


Figure 4 Demand sites branches

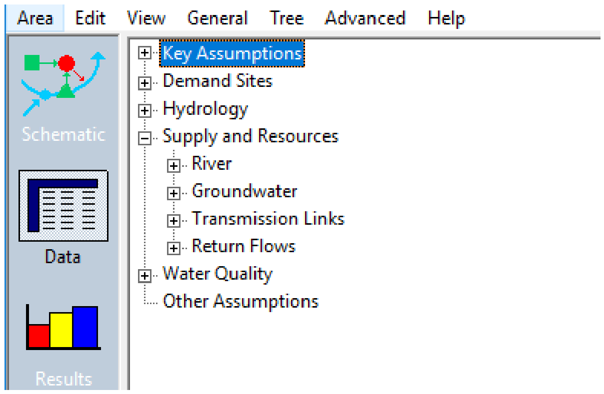


Figure 5 Supply and Resources branches

2. ARAGVI RIVER BASIN PLANNING MODEL

Data for the Aragvi model has been collected from numerous sources. The main data sources for the different components of the mode are: (1) water demand data comes from Ministry of Environment and Natural Resources Protection (MoENRP), Georgian Water and Power (GWP) Company, United Water Supply Company of Georgia (UWSCG), Ministry of Agriculture / Georgian Amelioration Company (GAC), Ministry of Energy and National Statistics Office of Georgia; (2) streamflow data was obtained from National Environmental Agency (NEA) and Georgian Water and Power(GWP) Company and; (3) inflows, outflows and reservoir storage was provided by Georgian Water and Power(GWP) Company (Reservoir owner company).

2.1. ARAGVI MODEL GEOGRAPHY

The Aragvi model includes the main stem of the Aragvi River and the main tributaries above Jinvali reservoir, Shavi Aragvi, Phshavi Aragvi and Khorkhula River (Figure 6).

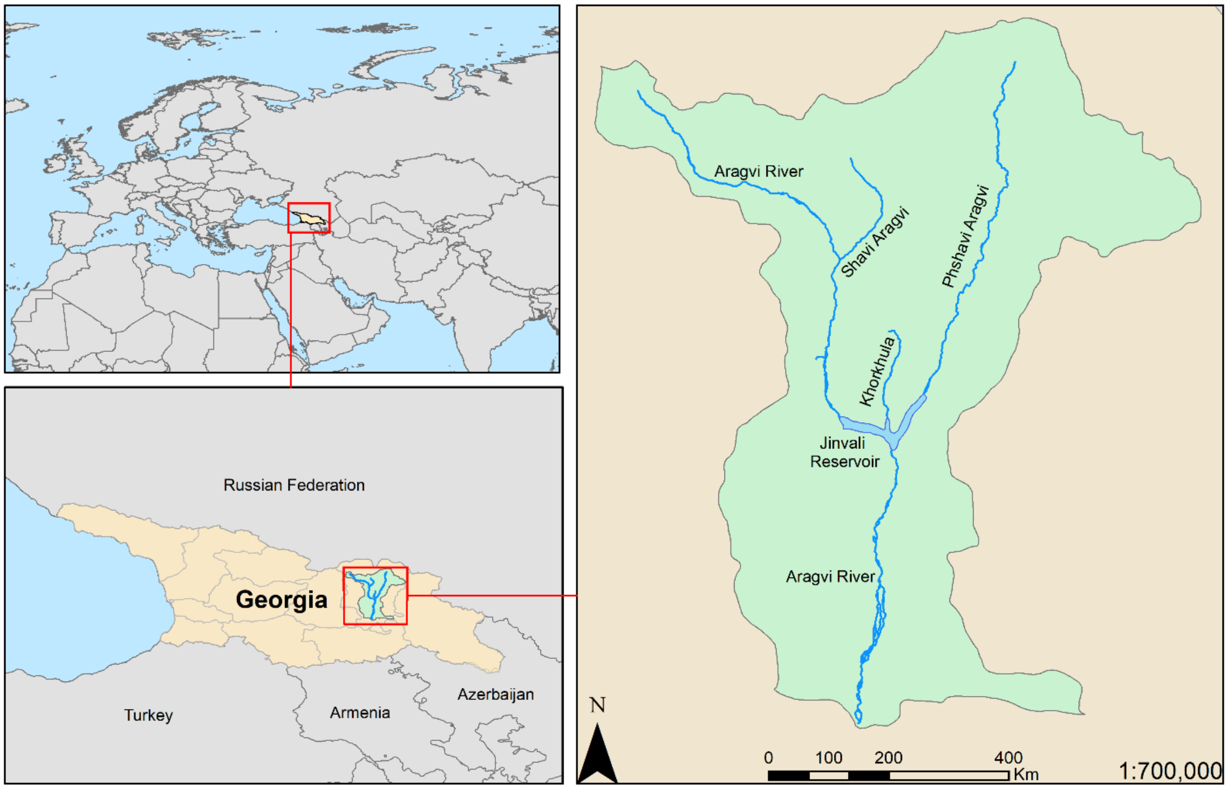


Figure 6 Main tributaries of the Aragvi River included in the WEAP Model

2.2. Streamflow Data

The Aragvi model has two monthly streamflow data time series that feed Jinvali reservoir:

1) Historic streamflow data (from January 1960 to December 1992) for four streamflow gauges are included in the model: Mleta, Pasanauri_T, Pasanauri_SH and Magoroskari.
2) Historic inflows into Jinvali reservoir (from January 1987 to December 2016) are included in the model.

The model has the ability to run with either of the two time-series data. The historic streamflow data is a more conservative time series data, in that the monthly and annual streamflow time series data has less water flowing into Jinvali reservoir (median annual flow of 1,277 million m3/year) than the historic time series data of inflows recorded into the Jinvali reservoir (median annual flow of 1,387 million m3/year).

Table 2 Historic streamflow data from four streamflow gages flowing into Jinvali reservoirs

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
min	31	26	36	73	146	108	78	59	49	42	38	36	**806**
0.9	52	48	79	212	306	264	206	152	103	96	79	68	**1,488**
0.75	50	44	64	177	260	223	171	128	89	76	65	57	**1,350**
0.5	44	40	58	149	225	199	141	98	75	68	55	50	**1,277**
0.25	39	35	52	118	177	173	126	88	59	56	46	43	**1,120**
0.1	35	31	47	89	156	151	101	71	51	52	42	40	**1,018**
max	59	53	96	249	525	375	248	165	159	102	106	98	**1,834**

Table 3Historic inflows recorded into Jinvali Reservoir. Units: million m³

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
min	30	21	28	74	62	106	82	56	38	34	34	23	**977**
0.9	69	55	150	260	455	358	236	171	127	120	109	86	**1,854**
0.75	56	51	104	223	372	298	192	124	103	96	82	66	**1,663**
0.5	46	38	78	203	281	241	155	102	83	78	69	55	**1,387**
0.25	40	33	55	133	229	203	124	84	64	59	54	47	**1,295**
0.1	35	28	40	103	167	152	89	69	58	49	47	38	**1,188**
max	89	77	206	357	646	619	278	257	168	210	194	106	**2,654**

The model includes a switch (user-defined variable in Key Assumptions/Hydrology/Switch) to select the input time series for the model. If the switch is equal to 0, the model uses streamflow data for headflows of Jinvali Reservoir only. If the switch is equal to 1 it uses streamflow data for headflows of Mleta, Pasanauri T, Pasanauri SH, Magaroskari, and the Incremental flows (IF) in between stations (Figure 7).

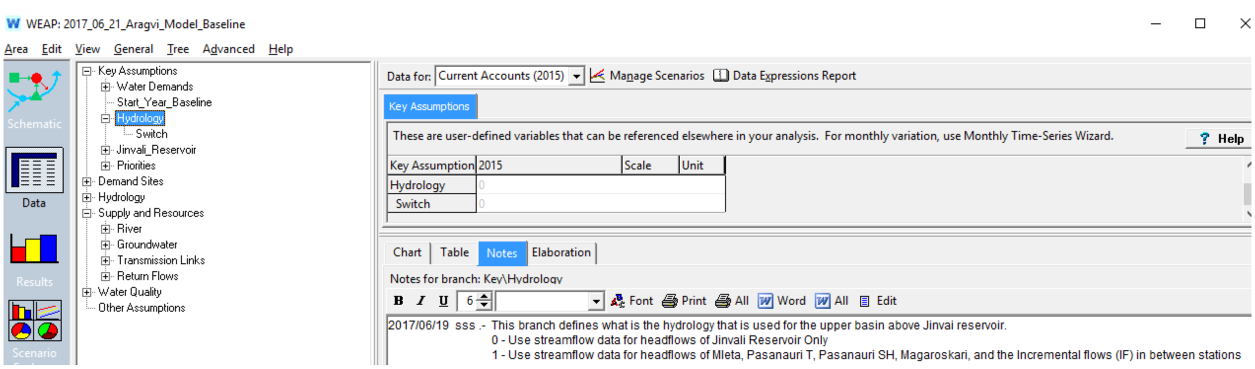


Figure 7 Switch to run the model with the historic streamflow data, or the historic inflows to Jinvali reservoir.

2.2.1. *SPECIAL STREAMFLOW CONSIDERATIONS*

We considered the principle of mass balance or both time series data.

1) For the historic streamflow data from four streamflow gauges, we calculated a mass balance in between gauge stations (Equation 1) to estimate incremental flows (IF_t). Incremental flows are the gains and losses of water that occur along the river mainstem in between gauge stations (Equation2).

$$\Delta(S_t) = I_t - O_t + IF_t \quad (1)$$

$$IF_t = O_t - I_t + S_t - S_{t-1} \quad (2)$$

2) For the historic inflows to Jinvali reservoir ($Inflows_t^{Jinvali}$), we calculated a mass balance for the inflows (I_t), outflows (O_t) and change of storage [$\Delta(S_t)=S_t-S_{t-1}$] (Equation 3) to estimate a mass balance correction (Equation 4). This correction was estimated because when a mass balance was performed using the raw data provided by the water agency, the mass balance principle was not met, most likely due to evaporation from the lake , or small errors in measuring the water coming out of the reservoir.

$$\Delta(S_t) = S_t - S_{t-1} = I_t - O_t + Correction_t \quad (3)$$

$$Correction_t = O_t - I_t + S_t - S_{t-1} \quad (4)$$

$$Inflows_t^{Jinvali} = Q_t^{Jinvali} + Correction_t \quad (5)$$

2.3. DEMAND SITES

There are 25 demand sites included in the Aragvi model. These demand sites include water use for domestic and municipal use (including Tbilisi and Dusheti), hydropower, irrigation and other uses. The Priority tab assigns each demand site a priority level ranging from 1 to 99. The model uses these priority levels when allocating water for the demand sites. The model will deliver water to all the level one priority sites and, if there is any water remaining in the system, it will then deliver water to the remaining priority levels. Level 1 is the highest demand priority for water in the system and all municipal users share this priority level (Table 5). This means that WEAP will try to satisfy all the demands at this level before any other level of priority demand. The Key Assumption/Priority branch contain all the specified priorities as shown in Figure 9.

Table 4 is a summary of the volume of water use and type of demand nodes. The largest consumptive water use is for the city of Tbilisi. The largest non-consumptive water use is for hydropower at Jinvali reservoir (Table 4).

Table 4 Average annual water demands by type in the Aragvi River WEAP Model.

Demand Type	Annual demand (mcm)
Urban and Domestic	152.608
Agriculture	79.479
Hydropower	496.300
Environmental/Sanitary	315.36
Other (mainly industrial)	16.859
Total	831.246
Consumptive demands	334.946

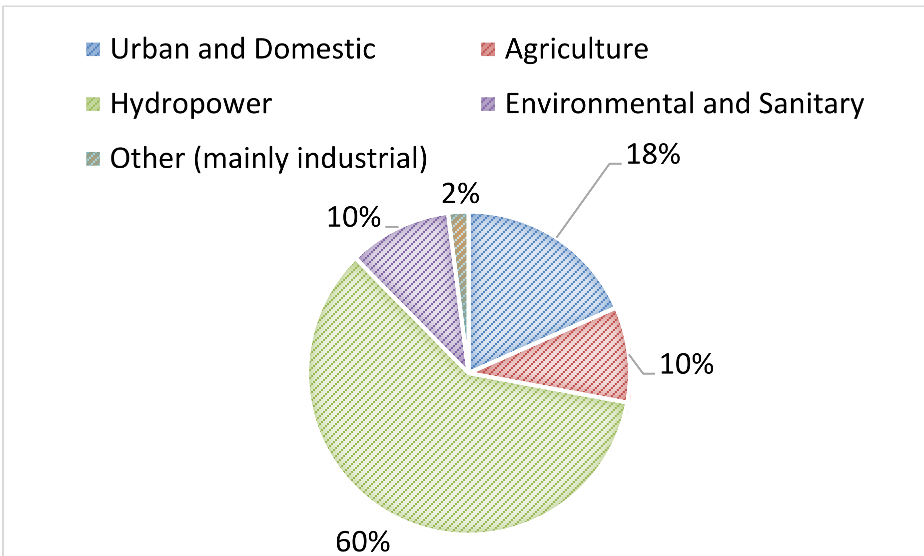


Figure 8 Water demands percentage distribution by type.

Table 5 Assigned priority levels for demands

Priority		Priority	
Urban and Domestic	1	Bodorna Reservoir	5
Hydropower	3	Agriculture	6
Environmental/Sanitary	2	Other	7
Jinvali Reservoir	4		

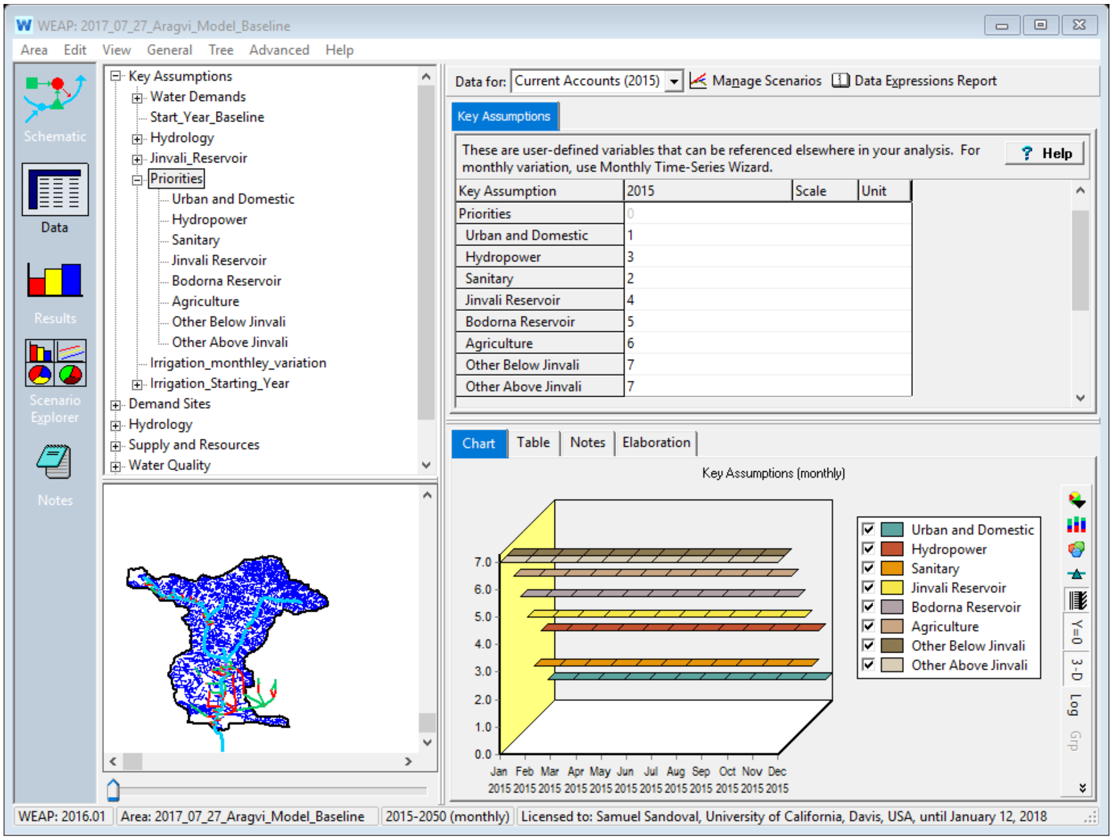


Figure 9 Priority levels within WEAP interface

The branch Key Assumption/Water Demands stores the annual water demands and water returns for every water demands declared in the model.

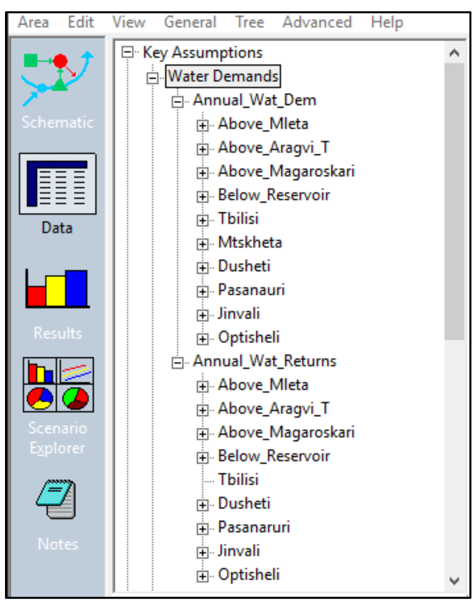


Figure 10 Water demands and water returns

2.3.1. TBILISI WATER DEMAND

We calculated the annual water demands from Tbilisi using the average water user per capita per day (liter per day per person lpd) and the population of the city (Equation 6). However, due to the conveyance losses to supply Tbilisi from its seven water sources (i), the actual water abstraction is greater than Tbilisi water demand. For each water demand, we estimated the required water abstraction considering the conveyance losses (Equation 8).

$$\text{Water Use}_{\text{t}}^{\text{Tbilisi}}[mcm] = \frac{\frac{(Population[cap] * Ldp[L] * 365)}{1000}}{1000000} \qquad \textbf{6}$$

$$\text{Water Use}_{\text{t}}^{\text{Tbilisi}}[mcm] = \sum_{i=1}^{i=7}\left[WaterAbstraction_t^i(1 - Conveyance\ Losses^i)\right] \qquad \textbf{7}$$

$$\text{Water Abstraction}_{\text{t}}^{\text{i}} = \frac{\text{WaterUse}_{\text{t}}^{\text{Tbilisi}} * ShareWaterSource^i}{(1 - Conveyance\ Losses^i)} \qquad \textbf{8}$$

The conveyance losses (*Conveyance Losses*^{i}) and share that each water sources (ShareWaterSourcesi) contributes to the total water use of Tbilisi (Water UsetTbilisi) was obtained from Source: "Georgian Water and Power" (GWP), United Water Supply Company (UWSCG) and Georgian Amelioration Company (GAC).

Table 6 Water supply sources for Mtskheta and Tbilisi

Source: "Georgian Water and Power" (GWP), United Water Supply Company (UWSCG) and Georgian Amelioration Company (GAC)

Company	Water supply type	The water intake source/basin and head building name	Distance from confluence	Take (mcm)	Use (mcm)	Conveyance losses (mcm)
GWP Mtskheta	Underground	The river Aragvi (near Mtskheta)	4	662.26	390.84	271.42
	Underground	The river Aragvi (near Mtskheta)	4	119.3	110.9	8.4
			Total	781.56	501.74	279.82
GWP Tbilisi	Underground	The river Aragvi (near Natakhtari)	6	31,752	13,859	17,893
	Underground	The river Aragvi (Bulachauri)	8	43,127	18,825	24,301
	Underground	The river Aragci (Natakhtari)	6	68,433	29,871	38,562
	Surface	The river Aragvi (Choporti)	23	56,516	24,671	31,845
	Underground	The river Aragvi (Mukharani)	4	13,773	6,013	7,760
	Surface	The river Aragvi (near Saguramo)	16	42,196	18,417	23,777
	Surface	The Jinvali reservoir* Bodorna buffer basin	6	328,320	65,688	262,632
			Total	584,117	177,344	406,773

Table 7 Tbilisi population 1959-2016

Year	Population
1959	761,391
1970	891,928
1979	1,056,140
1989	1,246,936
2014	1,108,900
2016	1,113,000

Table 8 Water demands included in Tbilisi water demand node

Tbilisi water sources	Average annual abstraction (mcm)
Jinvali and Bodorna Reservoir	328.32
Bulachauri	43.127
Choporti Misaktsieli	56.516
Saguramo	42.196
Mukhrani	13.773
Natakhtari	68.433
Natakhtari_new	31.752
Total Tbilisi water abstraction	584.117

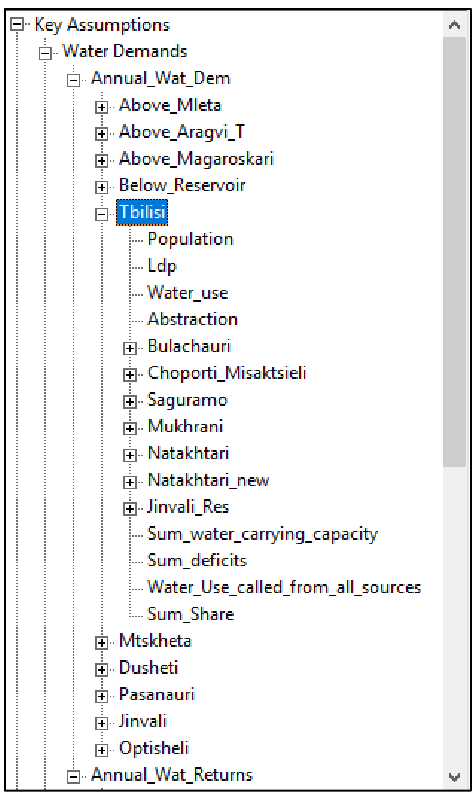


Figure 11 Tbilisi water demands in the model

Four conveyance systems supply water for Tbilisi, (1) from Jinvali Reservoir through Bodorna buffer, (2) Mukrani bypass, (3) Saguramo station, and (4) Natakhtari bypass (Figure 12).

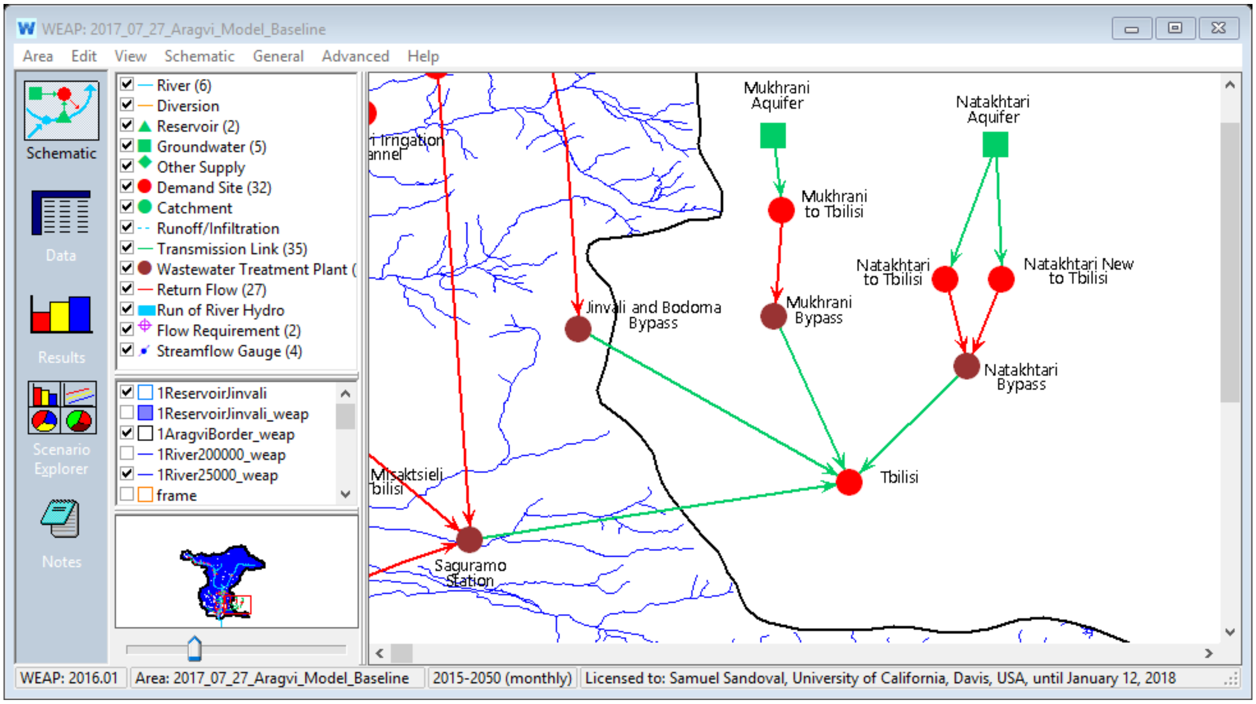


Figure 12 Water supply conveyance systems to Tbilisi

2.3.2. *Hydropower Water Demand*

The main hydropower object within Aragvi river basin is Zhinvali hydroelectric (generation) complex, which was put into operation in 1985. The area of water collection for the power site is up to 1,900 km^2.

The scheme of Zhinvali hydroelectric (generation) complex includes a seasonal storage reservoir, referred as Jinvali reservoir, with the capacity of 520 million m^3 for the needs of energy, water supply and irrigation.

The hydroelectric (generation) complex includes:

- Earth-and-rock-fill dam with the central loamy nucleus with the height of 101 m, the water intake, idle bottom culvert for the water flow of 1,000 m^3/sec.
- The intake structure (the height is 55 m) consists of a quadrangle reinforced concrete tower on the hard rock and is equipped with a small rack, flat wheel shield and grab bucket. The water runs from the water inlet through tunnel conduit with the length of 650 m to the turbines of underground power station.
- The power station is located behind the dam at the depth of 70 m under the riverbed. In the turbine room, there are 4 hydroelectric generators with the capacity of 32.5 thousand kW each. The power generated by the generators is transmitted to the open transformer yard of 110 and 220 kW at the downstream dam slope. The annual generation is 390 million kWh.

- The tailrace tunnel is gravity fed, passing 115 m^3/sec of water. It consists of 8.6 km tunnel area and 1.0 km tail-race at the end of which there is a compensating basin located in the tail-water for supplying the customers with water during the stoppage of hydropower as well as for the relaxation of rate of rise of water discharge in the riverbed of Aragvi with the sharp rate of loading at the hydro power.
- The capacity of compensating basin – Bodorna buffer basin (1 million m^3) is defined from the conditions of daily operation. The compensating basin is filled up at the expense of backwater of the river at 5 m, which is formed by 6.5 m dam and embankments of floodplain material.

The water consumers of natural flow of the river are the following: Mukhrani and Saguramo irrigation systems and springs of Aragvi group water supply of Tbilisi that is fed by filtrates of the River Aragvi. Part of the water runs to the main conduit of domestic and potable waters, which are combined with irrigation facilities.

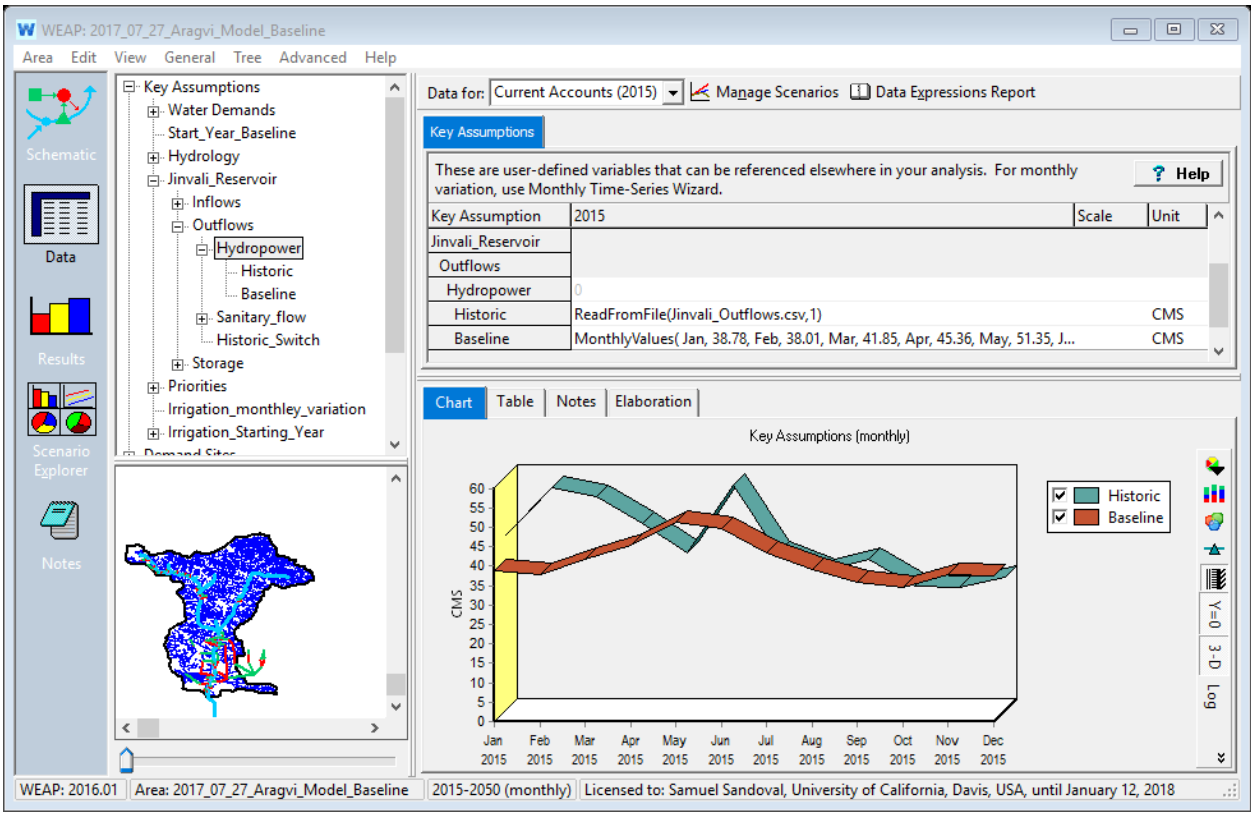


Figure 13 Hydropower releases from Jinvali Reservoir, Historic and Baseline

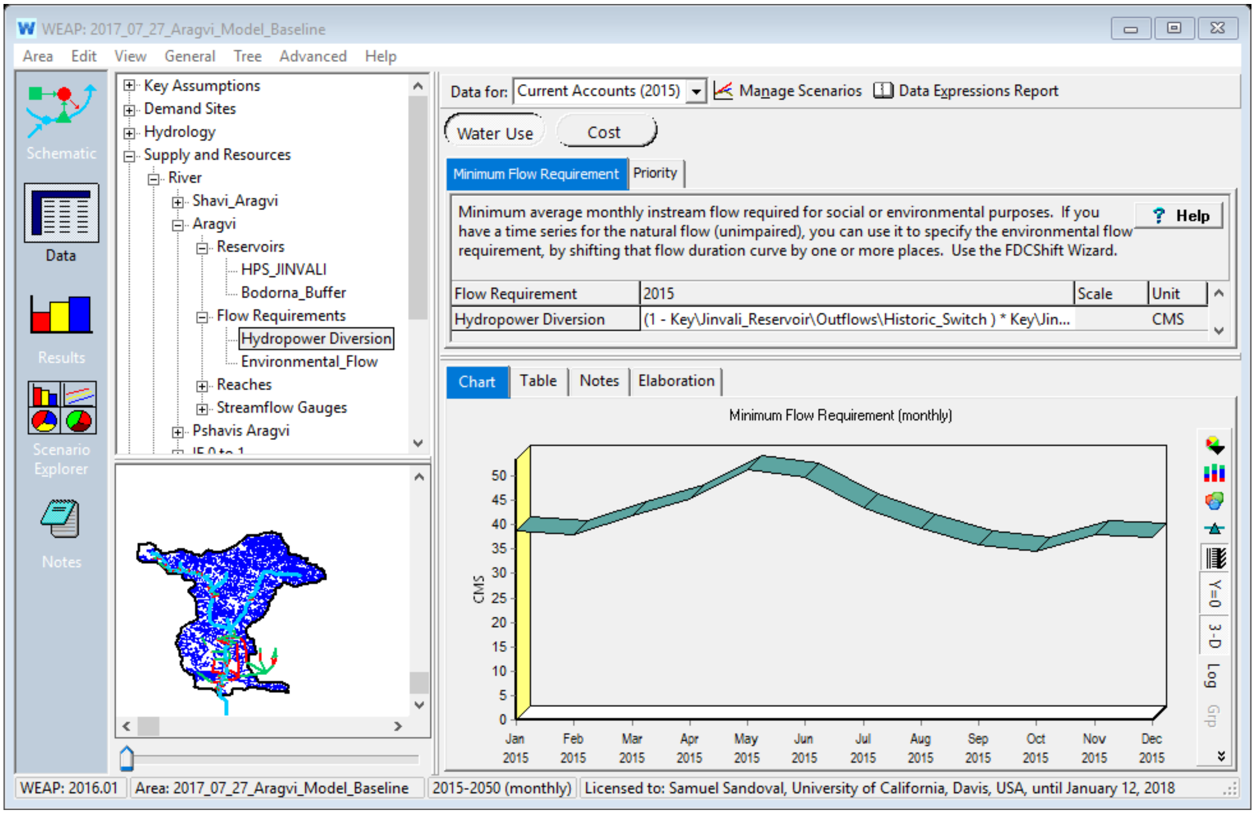


Figure 14 Hydropower diversion from Jinvali reservoir

2.3.3. *WATER DEMANDS ABOVE JINVALI*

In the model, the upper part of the basin mainly includes municipal, and industrial water demands. The cities integrated in the model are relatively small and therefore we considered a fixed annual demand with monthly variations. The industrial water demands include mainly water for building materials, and fish farms (Table 8). The set of water demands above Jinvali reservoir are only active when the streamflow data from the four streamflow gages is active (Key Assumption/Hydrology/Switch = 1).

There are two drinking water demand sites above Jinvali reservoir within the Aragvi River water allocation model. The first one is a small town of Pasanauri with 1,148 inhabitants (geostat, 2014). Pasanauri is supplied with surface water from Chabaruki River, which is a tributary of Aragvi River (supply source is Aragvi Riv. for our model). The household wastewater is collected from the Pasanauri sewerage collector and discharged in the Aragvi River. The second drinking water demand site is the village of Optisheli, located on the left bank of Aragvi River, which takes its water directly from Aragvi River.

Within the Aragvi River Basin there are two types of industries supplied by water from Aragvi River Basin - one contains full data (annual extraction, annual extraction limit and annual returns to the river) and another with only actual annual extraction without data about returns.

To estimate the return flow, companies were grouped according to their type of activity: Building Materials Production, Drinks Production, Fish Farms and Pools and Car Wash. Then the mean percentage of return flows was estimated by obtaining the average of industries that had return flows. It was assumed that this value was representative for the rest of the industries. Table 9 shows a list of the groups of industries, their annual water demand and return flows.

Table 9 Water demands, priority, and return flow above Jinvali reservoir.

#	Demand name	Annual demand (mcm)	Priority	Return flow (mcm)
1	Building Materials above Mleta	0.03038	Other Above Jinvali	0.025
2	Hotels Above Mleta	0.000458	Other Above Jinvali	0.000458
3	Fish farms Above Mleta	0.035	Other Above Jinvali	0.035
4	Building materials above Aragvi_T	1.397374	Other Above Jinvali	1.081597
5	Carwash above Aragvi_T	0.000021	Other Above Jinvali	0.000018
6	Fish farms Above Aragvi_T	0.288	Other Above Jinvali	0.288
7	Fish farms Above Mararoskari	0.0748	Other Above Jinvali	0.0748
8	Aragvi HPP	85	Other Above Jinvali	85
9	Pasanauri	0.93312	Urban and Domestic	0.839808
10	Optisheti	0.7776	Urban and Domestic	0

2.3.4. *WATER DEMANDS BELOW JINVALI*

There are six irrigation demands defined within the Aragvi river water allocation model, two of which are currently operational. The remaining four are currently not functional, but the Amelioration Company of Georgia has plans to incentivize their rehabilitation. Saguramo Irrigation system and Lami Misaktsieli Irrigiation System are the two systems that are currently functional. Saguramo Irrigation System is a small agricultural area of about 2,663 hectares. Lami Misaktsieli Irrigation System has an area of 7,985 hectares and a higher water demand than Saguramo. Together their annual water demand is 26.609 mcm, a relatively small demand when compared to the city of Tbilisi.

The non-functional irrigation systems are:

1) Bulachauri irrigation channel with an irrigated area of 232 ha, it is planned to be rehabilitated in 2018
2) Aragvispiri irrigation channel with an irrigated area of 385 ha, it is planned to be rehabilitated in 2019)
3) Narekvavi -Mchadijvari irrigation system with an irrigated area of 1,284 ha, it is planned to be rehabilitated in 2019
4) Bagichali irrigation system with an irrigated area of 1,189 ha, it is planned to be rehabilitated after 2021

Together after rehabilitation they will represent an annual water demand of 8.677 mcm, which is relatively small when compared with other demands in the basin.

Additionally, there are two municipal water demands downstream of Jinvali Reservoir. The city of Jinvali, a small town of 1,828 inhabitants (GEOSTAT, 2016) that diverts water from Bodorna buffer infiltration basin. The City of Jinvali has sewerage system that discharges its wastewater directly into the Aragvi River. The city of Dusheti is the larger town in the Basin with 6,167 inhabitants (GEOSTAT, 2016). Dusheti has two sources for drinking water, groundwater and surface water from Aragvi River which alone supplies up to 45% of the Dusheti population. The sewerage system does not cover the extent of Dusheti and the household wastewater is discharged into the Dushetiskhevi River (a tributary of the Aragvi River). Households with no connection to the sewer system discharge their wastewater into septic tanks.

A similar approach was used to estimate the water demand and return flows for industries below the reservoir, as it was used for the industries upstream of Jinvali reservoir. Industries were grouped according to their type of activity and annual water use and return flow were calculated. Table 10 shows a detailed list of grouped industries, their annual water use and return flows.

Table 10 Water demands, priority, and return flow below Jinvali reservoir.

Demand name	Annual Water Use (mcm)	Priority	Return flow (mcm)
Building Materials below reservoir	14.584593	Other Below Jinvali	0.888873
Drinking products below reservoir_SW	0.402868	Other Below Jinvali	0.30107
Drinking water below reservoir_GW	0.00208	Other Below Jinvali	0.001479
Carwash below reservoir	0.004548	Other Below Jinvali	0.00379
Fish farms below reservoirs	0.03912	Other Below Jinvali	0.03912
Dusheti	1.7804	Urban and Domestic	0.746496
Saguramo irrigation system	0.594	Agriculture	50.25
Lami misaktsieli irrigation system	70.185	Agriculture	24.79
Bulachauri irrigation channel	0.834	Agriculture	0
Aragvispiri irrigation channel	1.385	Agriculture	0
Narekvavi -Mchadijvari irrigation system	2.178	Agriculture	0
Bagichali irrigation system	4.280	Agriculture	0
Jinvali	0.43	Sanitary	0

2.3.5. Environmental/Sanitary Water Demands

There are two environmental water demands below Jinvali reservoir. First, the sanitary outflow demand derived directly from Jinvali reservoir, and released without passing through the turbines. It value is set fix throughout the period of analysis (POA), and it was estimated as the median monthly extraction that occurred in Jinvali reservoir from 1997 to 2016 (Table 11). This period was selected, since the reservoir was operated under standard operation rules.

Table 11 Sanitary water demand from Jinvali reservoir. Units: million m^3/month

	Jan	Feb	Ma	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Sanitary Flow	5	5	5	7	10	16	8	8	6	6	5	5

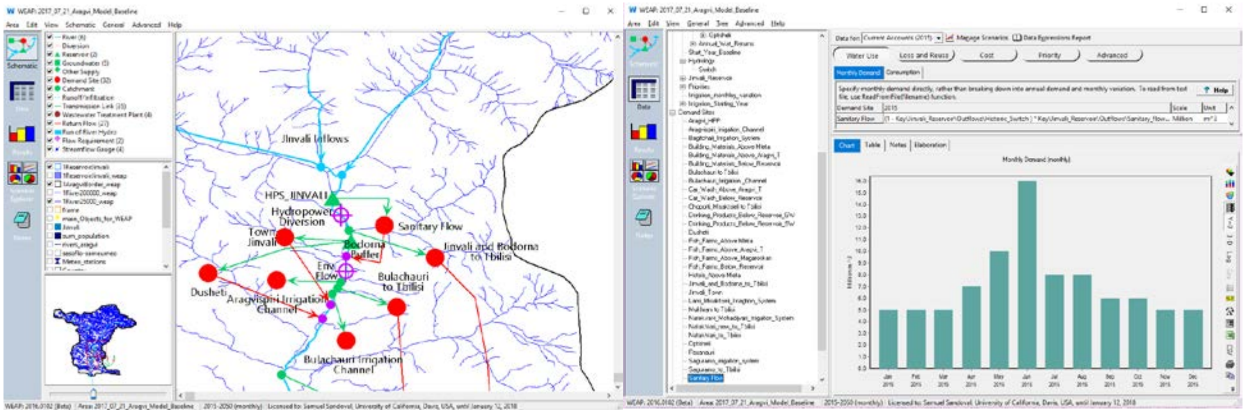


Figure 15 Sanitary diversion from Jinvali reservoir

In addition, there is an Environmental water demand along the Aragvi River mainsteam, just downstream of Bodorna Buffer reservoir. This water demands was set as a minimum flow requirement of 10 m^3/s at all times.

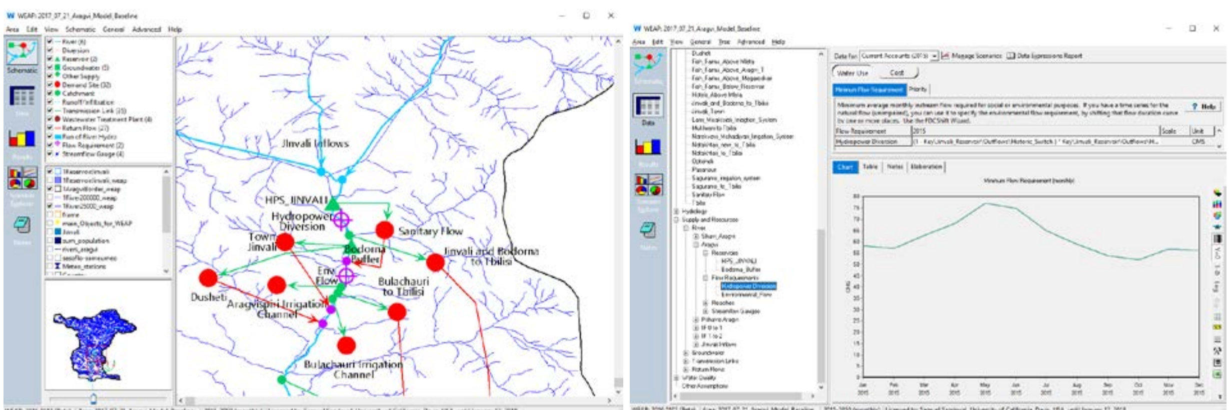


Figure 16 Sanitary diversion from Jinvali reservoir

2.1. SUPPLY AND RESOURCES

Supply and Resources data are broken into four sections in WEAP: River, Groundwater, Transmission Links, and Return Flows.

The first section of the Supply and Resources branch, *River*, has a branch for every tributary in the model and for all of the incremental flow sites (Figure 17). Each tributary has four branches: Reservoirs, Flow Requirements, Reaches, and Streamflow Gauges. Figure 17 shows the four sub-tabs for the Aragvi River branch located in *Supply and Resources/River/Aragvi*.

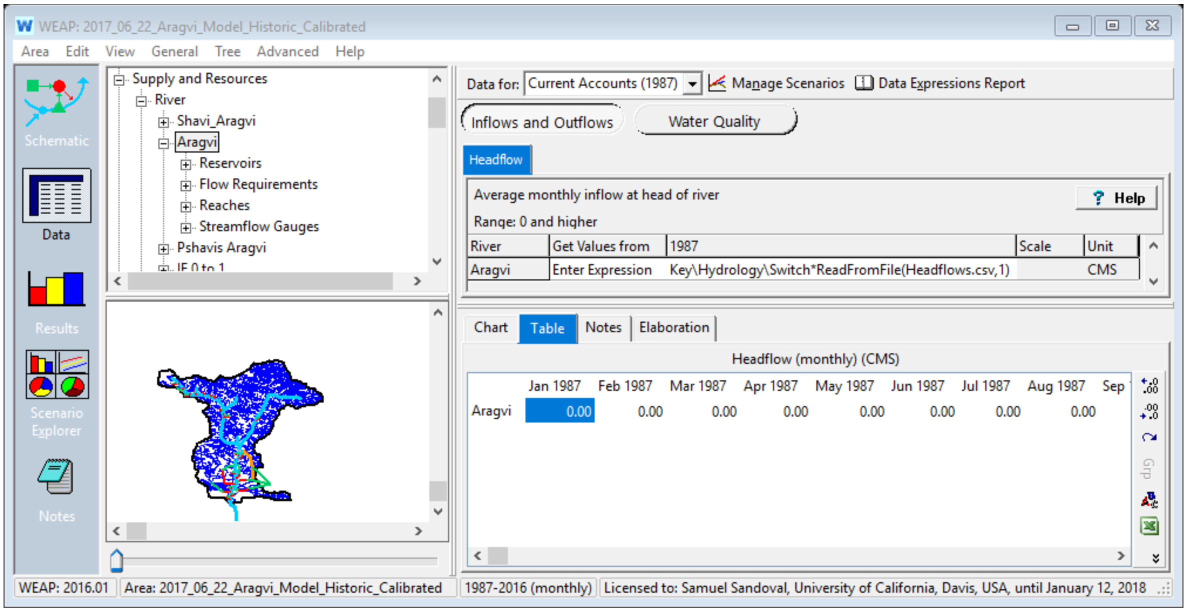


Figure 17 Aragvi River Example of Supply and Resources tab

The second section of the Supply and Resources branch, *Groundwater*, contains data for the groundwater nodes in the model, however it is merely set up for future inclusion and therefore not discussed at length in this model.

The third branch, *Transmission Links*, has a branch for every demand site in the model and there are three tabs for this field: Linking Rules, Losses, and Cost (Figure 18). Data are available for the linking rules, which in turn have three sub-tabs: Supply Preference, Maximum Flow Volume, and Maximum Flow Percent of Demand. Figure 13 shows the linking rules for the Tbilisi demand site as an example. The last section, *Return Flows*, contains data for any gains returning from the demand sites after consumption.

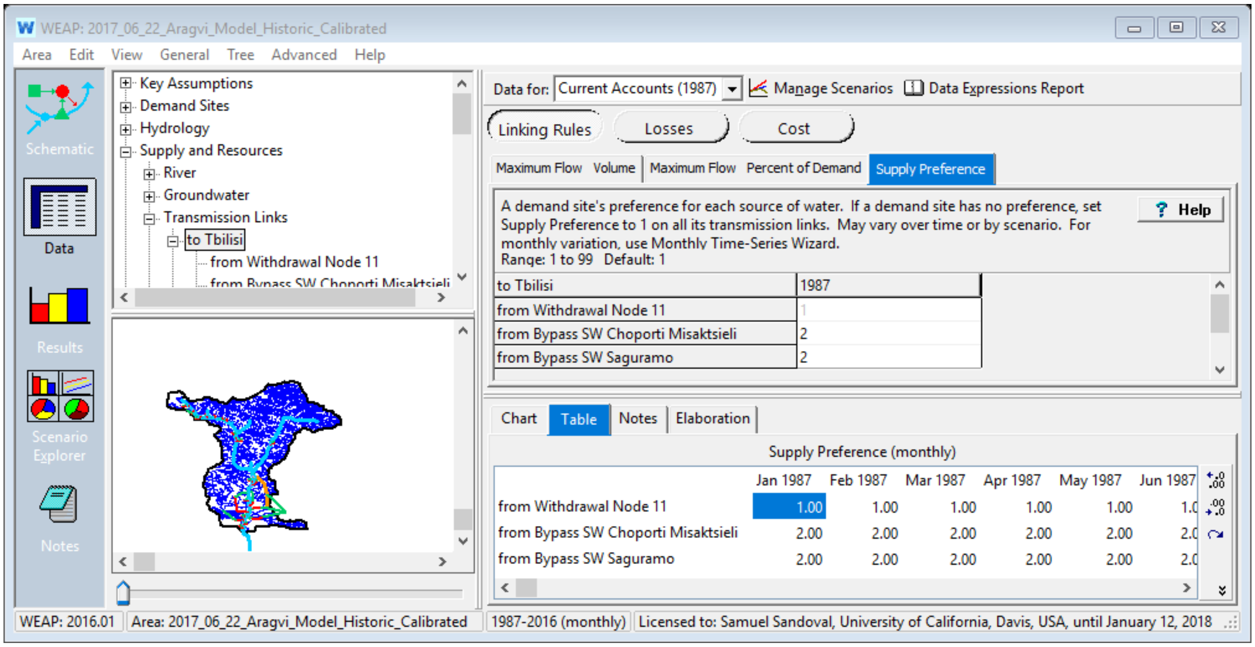


Figure 18 Tbilisi example of Transmission Links and Linking Rules.

2.1.1. *Jinvali and Bodorna Buffer Reservoirs*

We include the following characteristics for each reservoir into the model: Storage Capacity, Top of Conservation, and Top of Inactive (Table 12). The Top of the Buffer was set equal to the Top of Inactive for both reservoirs.

Table 12 WEAP Inputs for Reservoir Characteristics.

No.	Location	Reservoir Name	Storage Capacity (mcm)	Top Of Conservation (mcm)	Top of Inactive (mcm)
1	42.135852, 44.772349	Jinvali	520	520	106
2	42.131341, 44.774412	Bodorna	1	1	0
	1. Source: Information provided by GWP.				

The information for Jinvali Reservoir is located in three areas in the model: (1) Supply and Resources, (2) Key Assumptions/Jinvali_Reservoir, and (3) Key Assumptions/Priorities. *Supply and Resources* contains the reservoir characteristics, such as: Storage Capacity, Initial Storage, Volume Elevation Curve, Net Evaporation, Top of Conservation, Top of Buffer, Top of Inactive, Buffer Coefficient, and Priority. These are located under the Physical (Figure 19), Operation (Figure 20), and Priority (Figure 22). Jinvali reservoir has a priority of 4 (Key Assumption/Priority/Jinvali Reservoir). The rationale for this priority is that Jinvali can supply water for urban and domestic water use (Priority = 1), sanitary/environmental (Priority = 2) and Hydropower (Priority = 3) but not to other water users. Using a variable in Key Assumptions *(Key/Jinvali_reservoir/Storage/Initial_Storage)*, the initial storage of each reservoir is set to half of the conservation capacity. The volume-elevation curve for Jinvali reservoir relates the area-elevation and volume (Figure 19).

Table 13 Volume and elevation data for Jinvali reservoir.

Volume (mcm)	Elevation (m)	Volume (mcm)	Elevation (m)	Volume (mcm)	Elevation (m)	Volume (mcm)	Elevation (m)
0	720	39.2	744	150.7	768	335.3	792
0.5	722	45.7	746	163.3	770	353.8	794
1.5	724	52.8	748	176.3	772	372.9	796
3	726	60.3	750	189.9	774	392.5	798
5	728	68.3	752	204	776	412	800
7.5	730	76.9	754	218.8	778	432.9	802
10.6	732	85.9	756	234.1	780	454	804
14.1	734	95.5	758	249.9	782	475.4	806
18.1	736	105.5	760	265.9	784	497.4	808
22.6	738	116.1	762	282.5	786	520	810
27.6	740	127.1	764	299.6	788		
33.2	742	138.7	766	317.2	790		

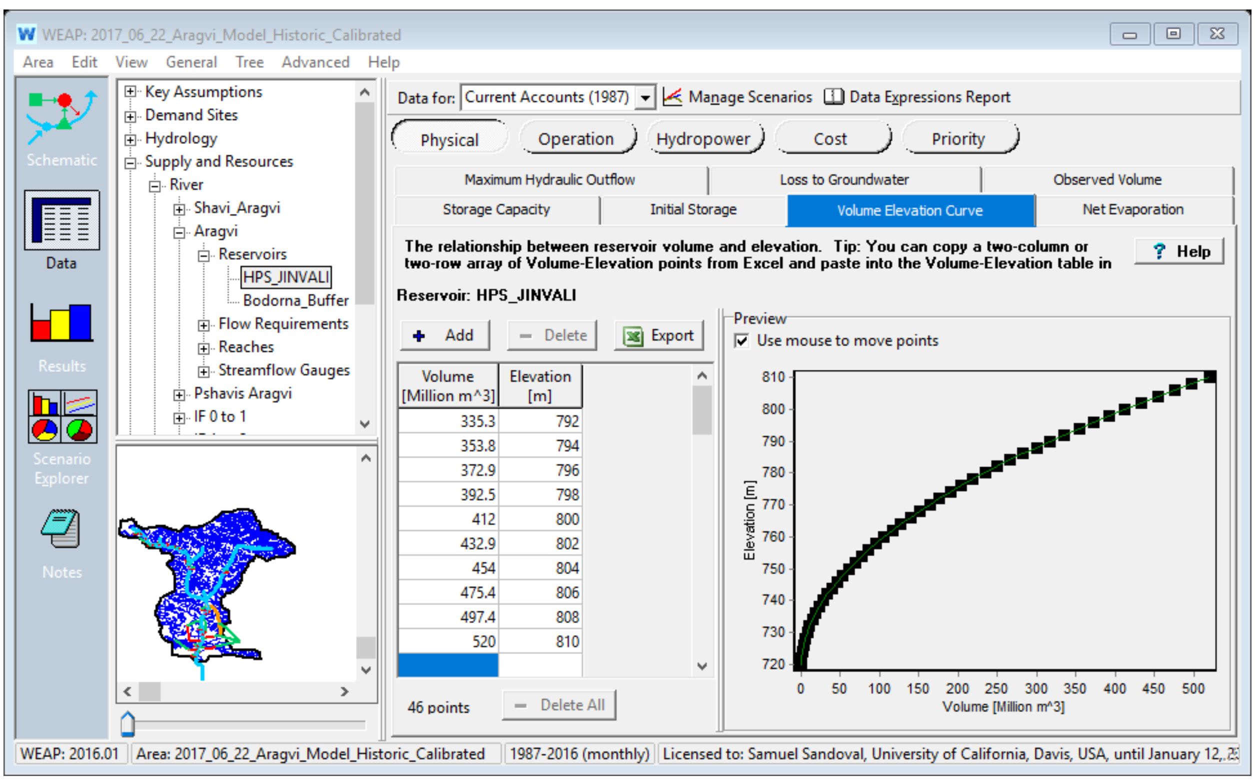


Figure 19 Volume elevation curve for Jinvali reservoir

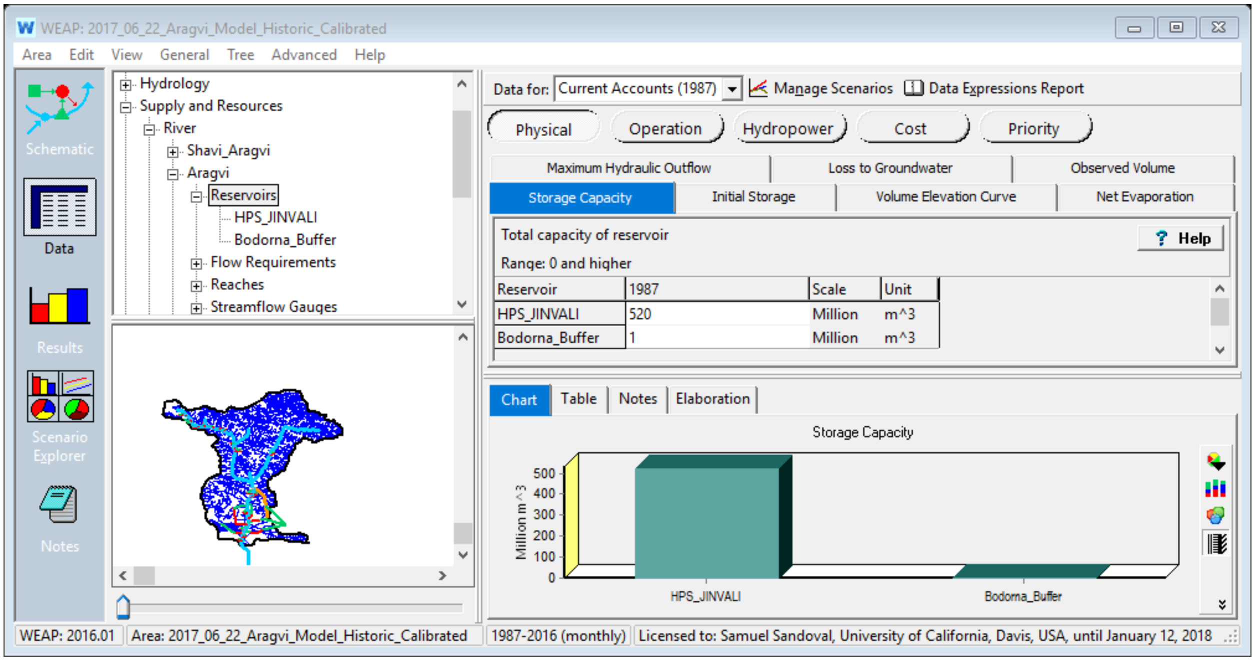


Figure 20 Physical tab example under Supply and Resources in WEAP

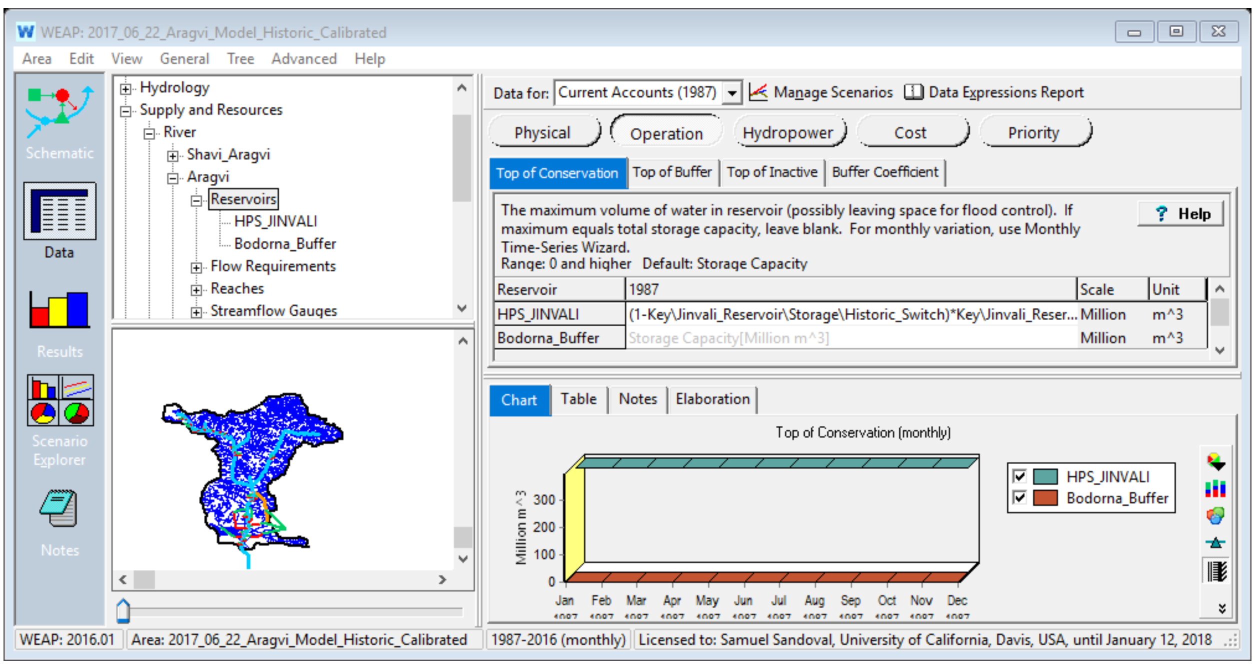


Figure 21 Operational tab example under Supply and Resources in WEAP.

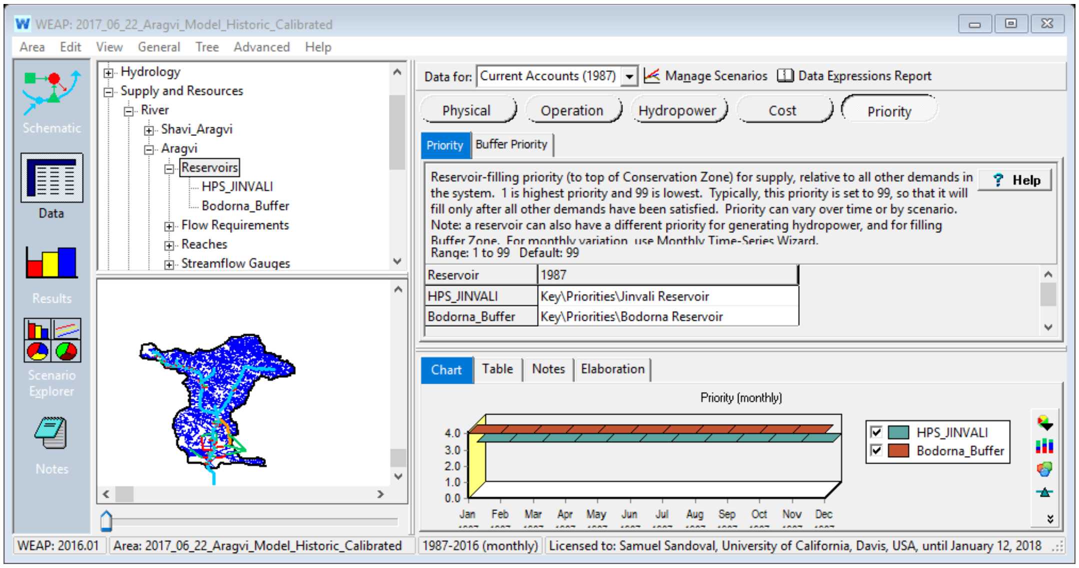


Figure 22 Reservoir Priority tab example under Supply and Resources in WEAP.

The information for Bodorna Buffer Reservoir is located in two areas in the model: (1) Supply and Resources; and (2) Key Assumptions/Priorities. *Supply and Resources* contains the reservoir characteristics, such as: Storage Capacity, Initial Storage, Volume Elevation Curve, Net Evaporation, Top of Conservation, Top of Buffer, Top of Inactive, Buffer Coefficient, and Priority. These are located under the Physical (Figure 19), Operation (Figure 20), and Priority (Figure 22). Bodorna Buffer Reservoir has a priority of 5 (Key Assumption/Priority/Bodorna Reservoir). The rationale for this priority is that Bodorna Reservoir can supply water for urban and domestic water use (Priority = 1) but not to other water users.

2.1.2. Linking Supply and Demand

Linking Rules under *Linking Demands and Supplies* are used to represent transmission losses or to constrain water deliveries to demand sites. In the model, some water demands have Linking Rules to represent transmission losses (Table 14).

Table 14 Conveyance losses uploaded in the Transmission links from water sources of Tbilisi Source: Georgian Water and Power (GWP), United Water Supply Company (UWSCG) and Georgian Amelioration Company (GAC)

From Demand	Losses from the System (%)
Jinvali Reservoir	79.99
Bulacahri	56.35
Choporti	56.35
Saguramo	56.35
Mukhrani	56.34
Natakhtari	56.35
Natakhtari New	56.35

3. MODEL TESTING

Model verification and testing is the next step in evaluating confidence in the model and the model data that have been discussed in the previous section. For this purpose, a *Historic Run* was developed considering the historic inflows, outflows and storage from Jinvali reservoir. This scenario varies from the actual management policies currently in use in the Aragvi basin that are set in the *Baseline Scenario*.

For testing, model reservoir storage values were compared to historical values. To assess the goodness of fit of the model, we calculated well common parameters such as the Index of Agreement, Coefficient of Efficiency, and Pearson's correlation.

3.1. HISTORIC RUN

A 29 year hydrologic POA was used to evaluate the accuracy of the model in the Historic run, from Jan/1987 to Dec/2016. This period was selected because measured data for inflows, outflows and storage was available.

3.2. COMPARISON OF WATER STORAGE

Figure 23 show a comparison of the water storage in Jinvali reservoir for the POA. The goodness of fit parameters considered are the Pearson's Correlation, the Coefficient of Determination, the Index of Agreement (Willmott), and the Coefficient of Efficiency (Nash) (Table 15).

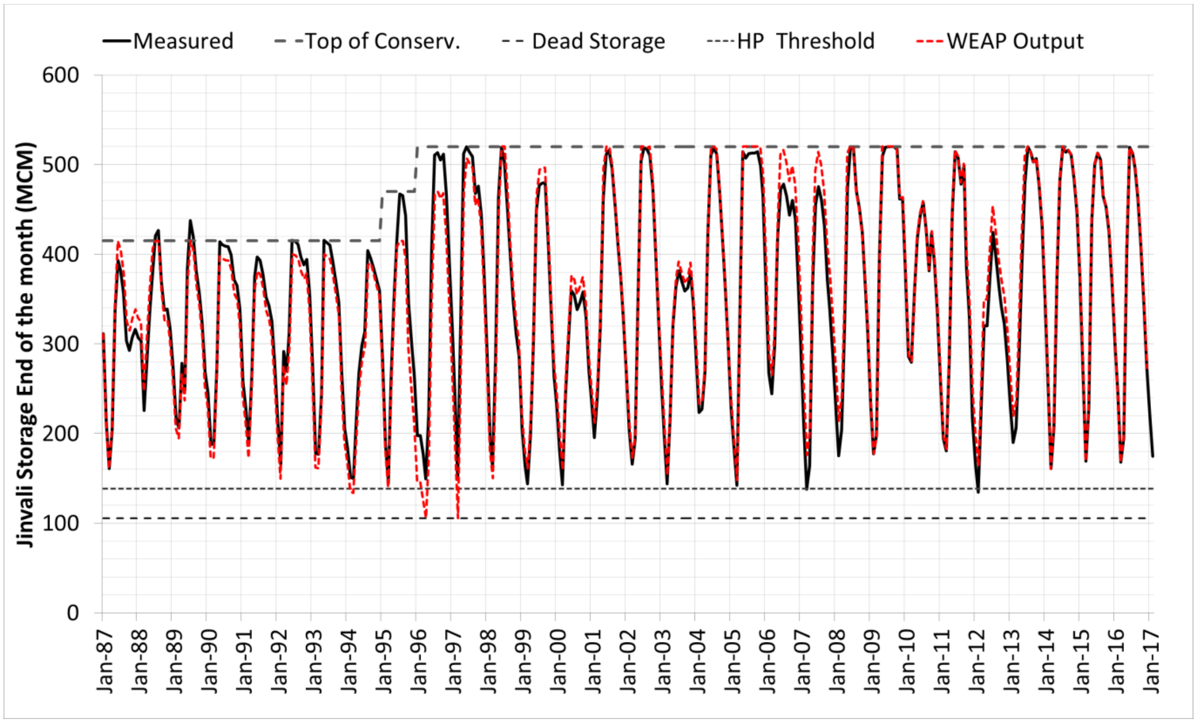


Figure 23 Measured and calculated storage in Jinvali reservoir for the period of analysis (POA).

Table 15 Jinvali storage performance coefficients for the model.

Pearson's Correlation	0.985
Coefficient of Determination	0.970
Index of Agreement (Willmott)	0.990
Coefficient of Efficiency (Nash)	0.940

3.3. Comparison of Hydropower generation

Figure 24 shows a comparison of the hydropower generation from Jinvali reservoir for the POA. The same goodness of fit parameters as for the storage were considered (Table 16).

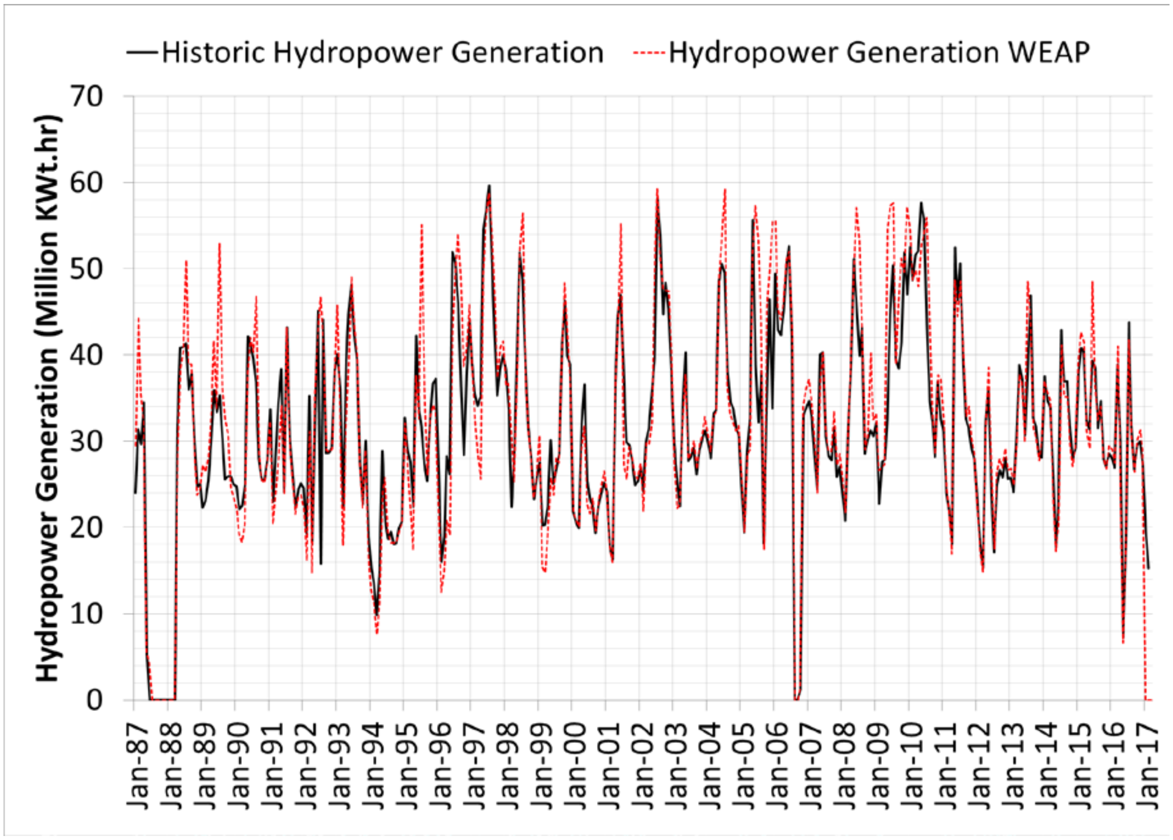


Figure 24 Measured and calculated hydropower generation in Jinvali reservoir for the POA.

Table 16 Jinvali hydropower performance coefficients for the model.

Pearson's Correlation	0.926
Coefficient of Determination	0.858
Index of Agreement (Willmott)	0.960
Coefficient of Efficiency (Nash)	0.830

4. STRATEGIES FOR WATER RESOURCES MANAGEMENT

This section explains the current water management and alternative water management strategies (called *Scenarios*) that were consider to be evaluated in the Aragvi model. Also, this section describes an interface that was developed for the Aragvi model, so users can easily modify and run their own strategies.

4.1. MODEL INTERFACE

The interface is a tool that links Excel to WEAP, and must be located in the folder: C\:WEAP Results (you may need to create the folder). Most of the programming to overlap the two software packages was primarily created using Microsoft Visual Basic for Applications (VBA), which allows for cells in an Excel Spreadsheet to be directly linked into variables declared in the Aragvi model developed in WEAP. Once a variable has been linked, values typed in an Excel spreadsheet can easily be changed, run in the Aragvi model, and the corresponding results can be retrieve from WEAP into the Excel spreadsheet. **The main objective for developing an interface is to create a user-friendly tool that will allow scientists, engineers and decision makers to explore their own ideas and strategies through an Excel interface**, which is a platform that is familiar to many people.

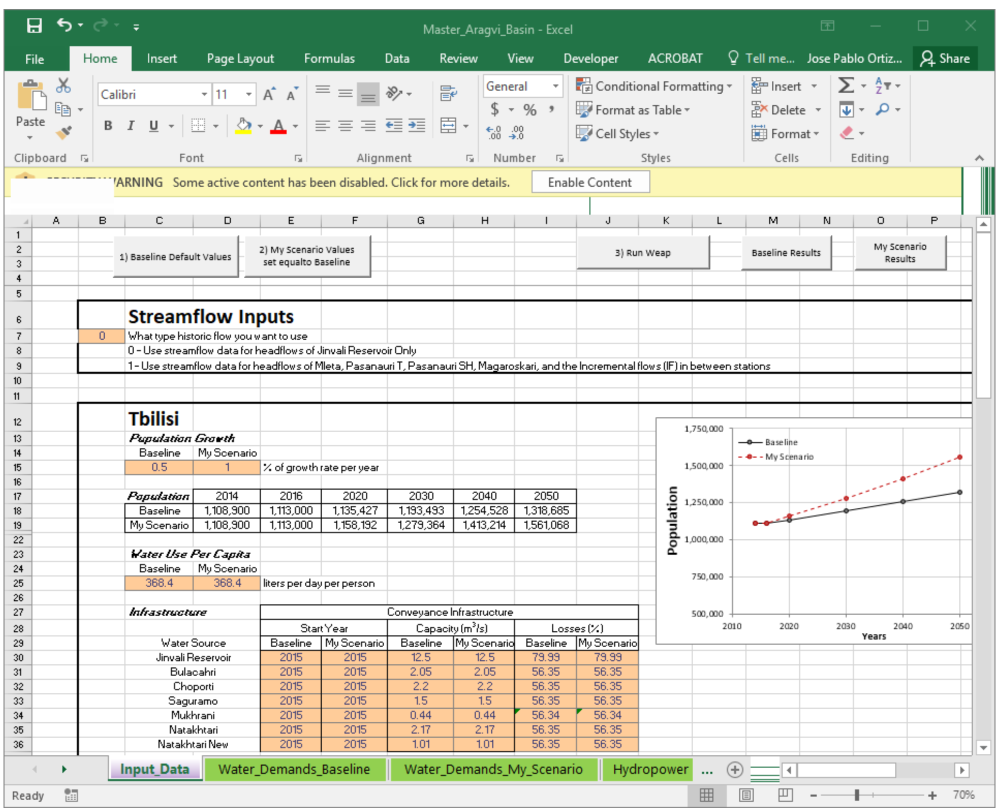


Figure 25 Excel interface example of the Aragvi model

The Master_Aragvi_Basin Excel spreadsheet is broken up into several components. The first sheet, “Input Data”, allows the user to input data and change variable to test for different scenarios in the Aragvi model. On this sheet there are five main components: Streamflow Input, Tbilisi, Agriculture, Hydropower and Priorities. In the Input Data sheet, all cells that are colored with a pink color mean their values are linked into the Aragvi model and therefore directly affect the parameters and results of the Aragvi model (Figure 25)

Under Streamflow input, the user can enter into cell “B7” either a 0, indicating the scenario will use data for headflows of Jinvali Reservoir only, or a 1 to signify the scenario will account for headflows from Mleta, Pasanauri, Pasanauri SH, Magaroskari and the incremental flows between stations.

The Tbilisi section of the sheet allows the user to set different percent growth rates of Tbilisi’s population in cells “C15” and “D15” for Baseline and My Scenario respectively. These growth rates then are illustrated on the corresponding graph located to the right of the population data. The user can also run scenarios representing a change in water demand. Under the heading “Water Use Per Capita”, the user can change the water use per capita values for both Baseline and My Scenario depending on how many liters/person/day are demanded. The final component for the Tbilisi section is “Infrastructure”. As seen in Figure 26, the user can manipulate the values of Conveyance Infrastructure’s start year, capacity and losses for each of the seven cities (Jinvali Reservoir, Bulachauri, Choporti, Saguramo, Mukhrani, Natakhtari and Natakhtari New).

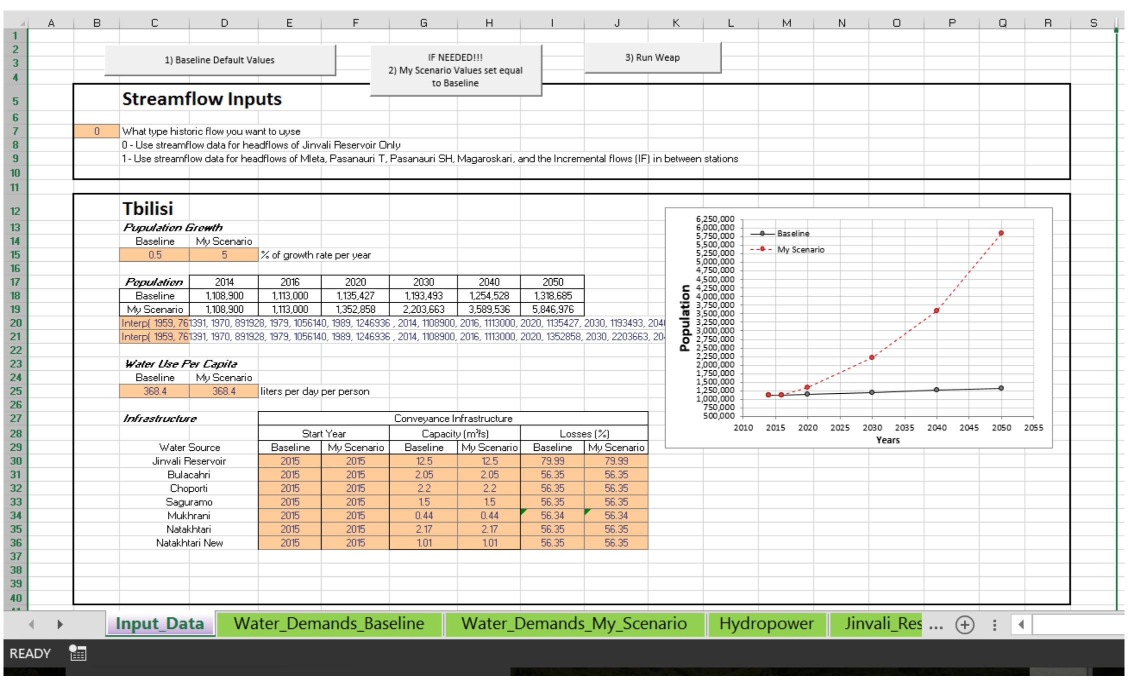
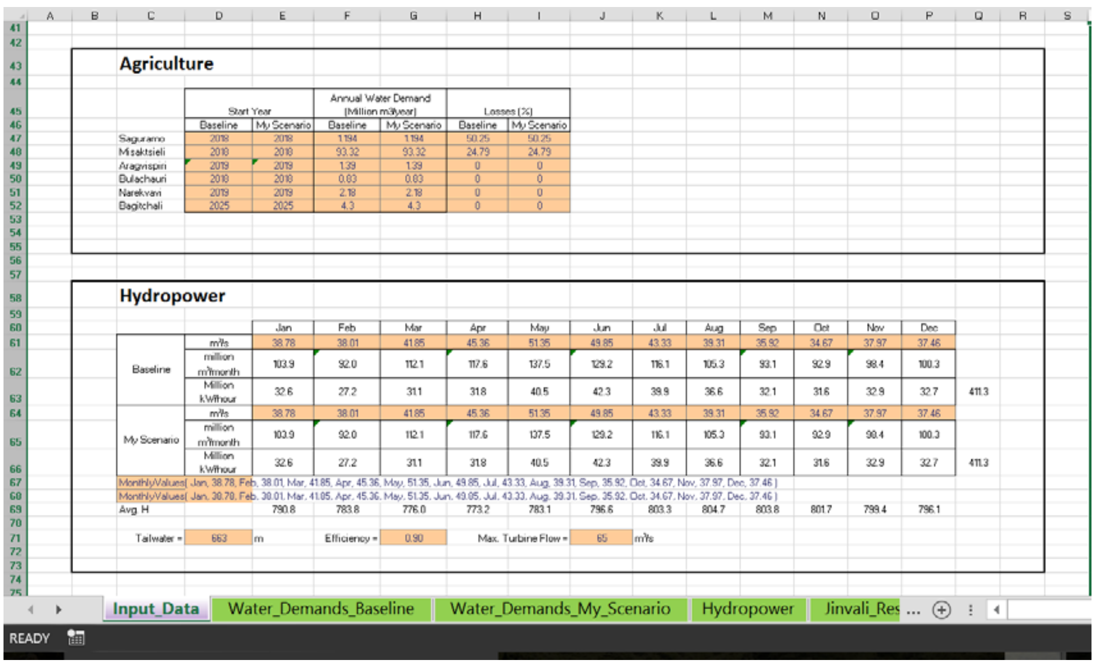


Figure 26 Streamflow and Tbilisi inputs on the Interface

The “Input_Data” sheet also accounts for information pertaining to Agriculture (Figure 27). Here, the user can enter values for variables on the start year, annual water demand and losses for both Baseline and My Scenario. These variables feed directly into the Aragvi model through the VBA programming, allowing users to easily see how changes in agriculture variables will affect their water supply and the effects of these demands into other water users.

The next section on the “Input_Data” sheet allows for consideration of hydropower variables (Figure 27). The user can change the values (m^3/s) of water flowing into the turbines for hydropower in cells “E61-P61” for Baseline and “E64-P64” for My Scenario. Additionally, the user can change the values for Tailwater, Efficiency and Maximum Turbine Flow of the hydropower plant. All three of the previously mentioned variables are linked to WEAP.



Agriculture

	Start Year		Annual Water Demand (Million m3/year)		Losses (%)	
	Baseline	My Scenario	Baseline	My Scenario	Baseline	My Scenario
Saguramo	2018	2018	1.194	1.194	50.25	50.25
Misaktsieli	2018	2018	93.32	93.32	24.79	24.79
Aragvispiri	2019	2019	1.39	1.39	0	0
Bulachauri	2018	2018	0.83	0.83	0	0
Narekvavi	2019	2019	2.18	2.18	0	0
Bagitchali	2025	2025	4.3	4.3	0	0

Hydropower

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Baseline	m³/s	38.78	38.01	41.85	45.36	51.35	49.85	43.33	39.31	35.92	34.67	37.97	37.46	
	million m³/month	103.9	92.0	112.1	117.6	137.5	129.2	116.1	105.3	93.1	92.9	98.4	100.3	
	Million kWh/hour	32.6	27.2	31.1	31.8	40.5	42.3	39.9	36.6	32.1	31.6	32.9	32.7	411.3
My Scenario	m³/s	38.78	38.01	41.85	45.36	51.35	49.85	43.33	39.31	35.92	34.67	37.97	37.46	
	million m³/month	103.9	92.0	112.1	117.6	137.5	129.2	116.1	105.3	93.1	92.9	98.4	100.3	
	Million kWh/hour	32.6	27.2	31.1	31.8	40.5	42.3	39.9	36.6	32.1	31.6	32.9	32.7	411.3

MonthlyValues(Jan, 38.78, Feb, 38.01, Mar, 41.85, Apr, 45.36, May, 51.35, Jun, 49.85, Jul, 43.33, Aug, 39.31, Sep, 35.92, Oct, 34.67, Nov, 37.97, Dec, 37.46)
MonthlyValues(Jan, 38.78, Feb, 38.01, Mar, 41.85, Apr, 45.36, May, 51.35, Jun, 49.85, Jul, 43.33, Aug, 39.31, Sep, 35.92, Oct, 34.67, Nov, 37.97, Dec, 37.46)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg. H	790.8	783.8	776.0	773.2	783.1	796.6	803.3	804.7	803.8	801.7	799.4	796.1

Tailwater = 663 m; Efficiency = 0.90; Max. Turbine Flow = 65 m³/s

Figure 27 Interface section for Agriculture and hydropower inputs

Finally, the last component of the “Input_Data” page is Priorities. Figure 28 shows that the priorities for different types of water users can be changed in this section. This can be used to compare how the water supply changes depending on the priority for different types of water users. For example, those with a water demand of 1 will be granted the highest priority, meaning their water demand will be met before water is allocated to other users. Each water user can have a rank of 1-99, and two or more users can share the same demand (in that instance water will be allocated equally among the users of that priority).

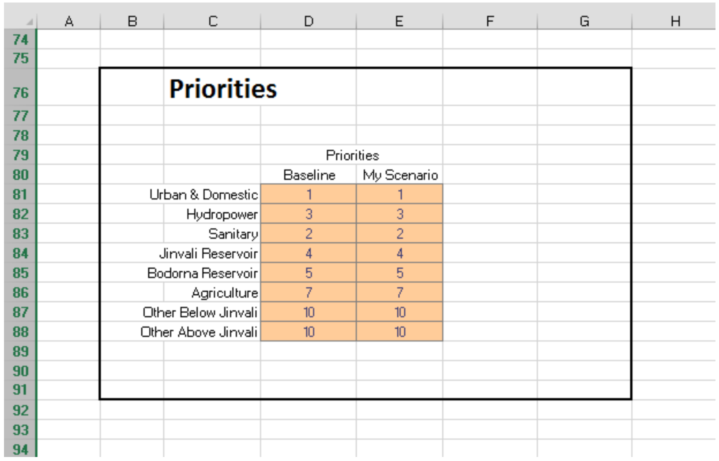


Figure 28 Priorities variable on the interface

All values for My Scenario are originally set to mirror those of the Baseline scenario. Baseline represents a business as usual stance on water use and population growth.

The Master_Aragvi_Basin Excel spreadsheet also has two sheets called "Water_Demands_Baseline" and "Water_Demands_My_Scenario" (Figure 29) which imports the results calculated in the Aragvi model and estimate the different performance criteria used to evaluate the water supply in the Aragvi river Basin.

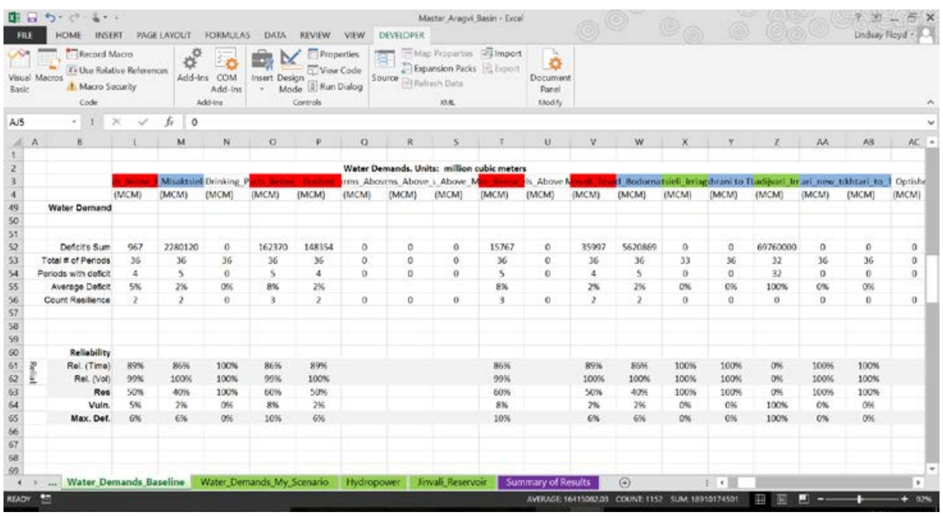


Figure 29 Water_Demands_Baseline sheet on the interface

Similarly, the sheet titled "Hydropower" follows the same procedure by importing the outputs of the Aragvi model and estimates the performance criteria used to evaluate the hydropower production in Jinvali reservoir (Figure 30).

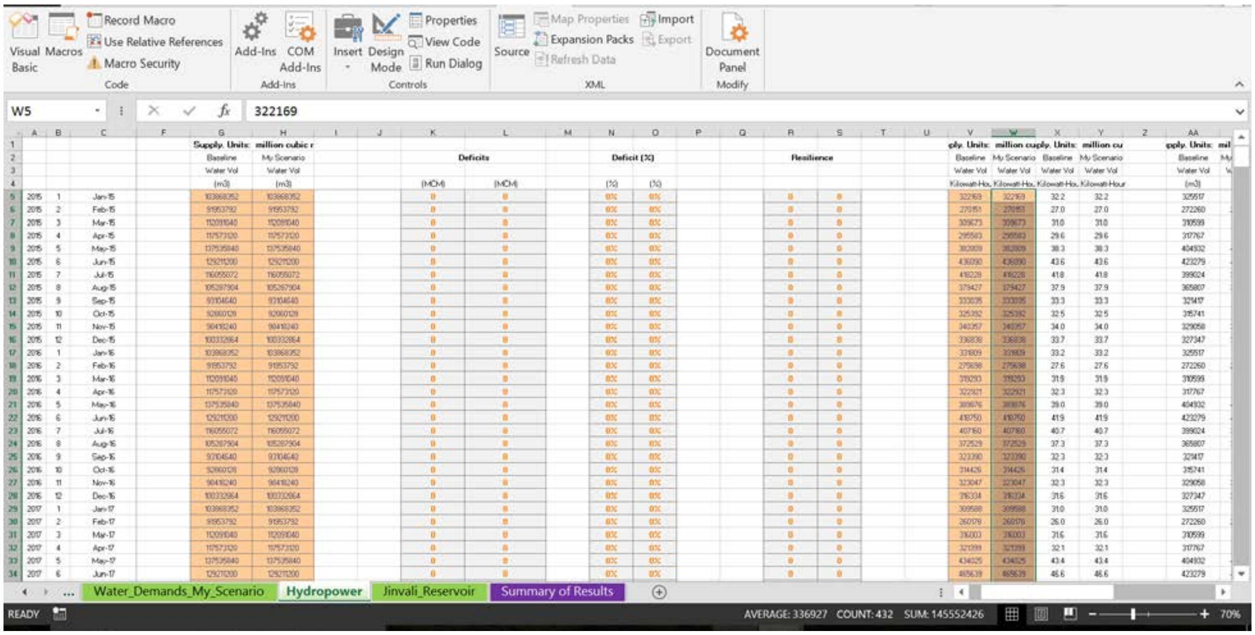


Figure 30 Hydropower results on the Master_Aragvi_Basin spreadsheet

Likewise, "Jinvali_Reservoir" is a sheet that imports the Jinvali reservoir storage outputs from the Aragvi model, from January 2015 to December 2050 (Figure 31). There are two distinct columns, the one on the right displays the values in million cubic meters (MCM) and the left column's units are in cubic meters (m^3).

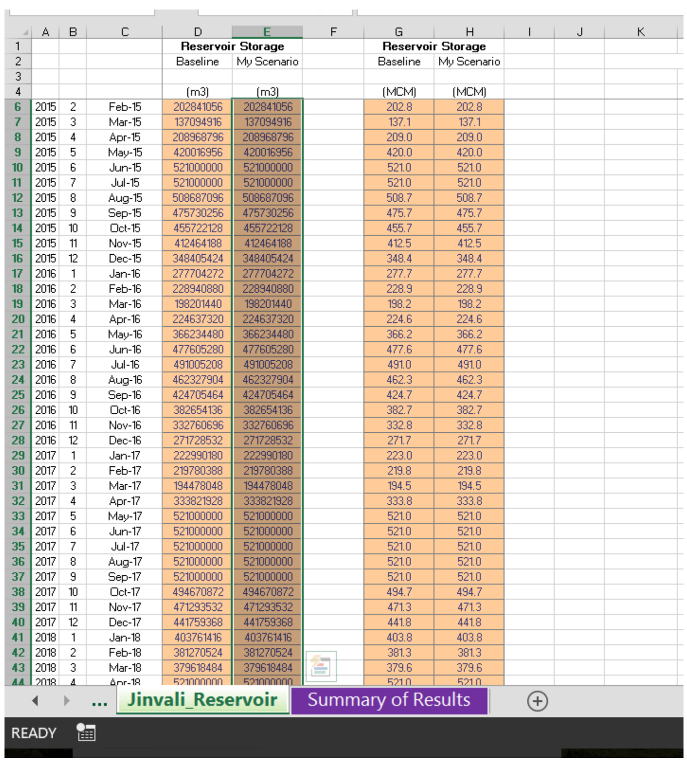


Figure 31 Jinvali Reservoir results in the interface. Left side is in m3 units, the right side is in MCM.

Finally, to view the result from all the previous sheets, the page titled “Summary of Results” displays four tables: one for Tbilisi, one for agriculture, one for water demands below Jinvali Reservoir and one for hydropower (Figure 32, Figure 33). Each of the tables offers a summary for both, the Baseline and My Scenario values that were declared in the Input Data sheet. Each summary includes percentages on the following factors: Reliability, Resilience, Vulnerability, Maximum Deficit and Sustainability Index. The corresponding graphs, located to the right of each table, illustrate the difference between the Baseline and My Scenario strategies considering the selected performance criteria.

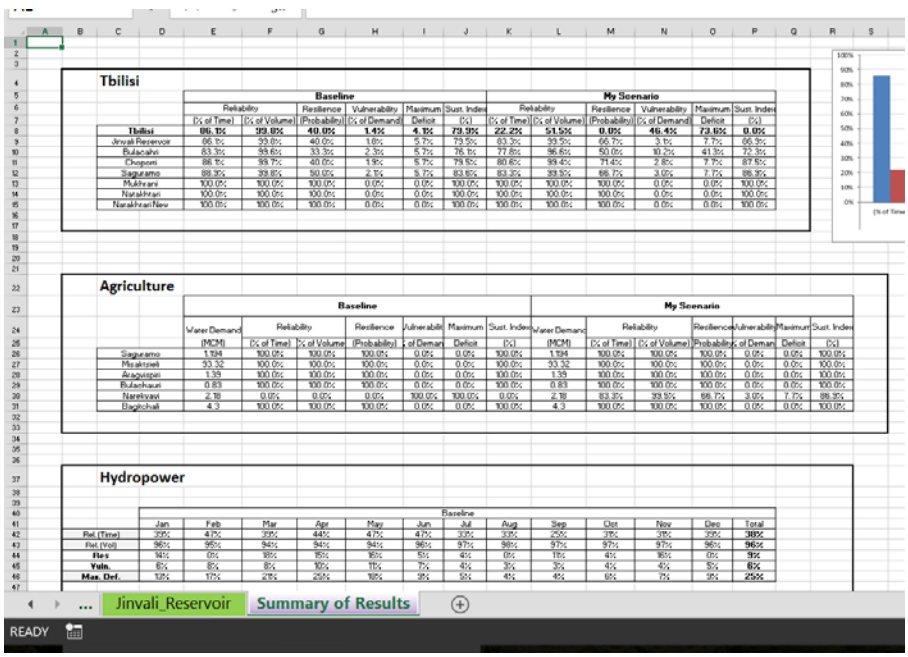


Figure 32 Summary of Results, tables for Tbilisi, Agriculture and Hydropower on interface

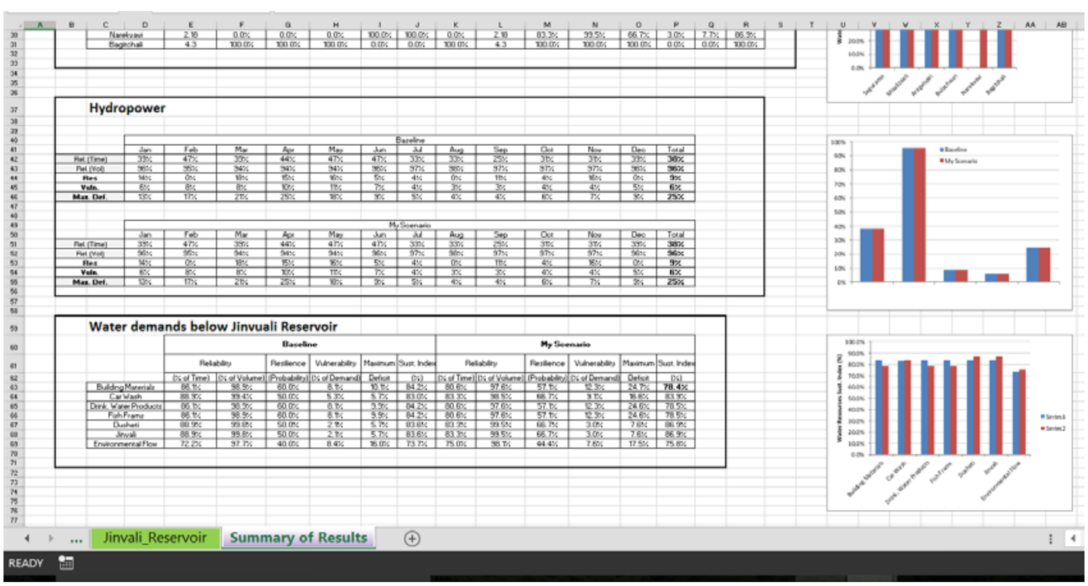


Figure 33 Summary of results sheet shown with tables and corresponding graphs on interface

4.2. PERFORMANCE CRITERIA

This section describes the performance criteria that are used to evaluate the response of water and electricity demands, and reservoir storage to different strategies considered in each scenario in the Aragvi model.

- ***Reliability - Time***: This criterion represents the percentage of time (the probability) that a water (or electricity) demand was fully supplied. For instance, a 75% reliability *in time* means that 75% of the POA a determined water user received its full allocation of the requested water demand. It can also be considered as the probability that a water user will receive its full allocation during the POA.
- ***Reliability - Volume***: This criterion represents the overall amount of water that a water user received, compared to the water demand requested in the POA, in percentage. For instance, an 80% reliability *in volume* means that a determined water user received 80% of the overall amount of water requested during the POA.
- ***Resilience***: This criterion represents the probability of recovery (of being fully supplied) once its water supply has failed (in this case its full water demand was not supplied). For instance, a resilience of 50% means that once a determined user is experiencing a water deficit (shortage in its full water supply), there is a 50% probability (one out of 2 times) that in the following year it will recover and will not experience any water deficit.
- ***Vulnerability***: This criterion represent if a water user experience a water deficit, what will be its average (expected) value. This criterion is used to quantify the severity of the water deficits that a determined water user can experience. For instance, a Vulnerability of 25% means that on average, when a water deficit occurs for that determined water user, the average deficit is 25% of its water demand.
- ***Maximum Deficit***: This criterion represents the worst water deficit that a water user can experience. This criterion is used to quantify the worst case scenario for a water deficit. For instance, a Maximum deficit of 35% means that the worst water deficit that a determined water user experienced during the POA was 35% of its water demand.
- ***Water Resources Sustainability Index (SI)***: This is an index that groups the five previous criteria into one single value. The SI is used as a summary index to evaluate and compare the overall performance of the Baseline and My Scenario strategies.

4.3. BUSINESS AS USUAL: BASELINE SCENARIO

The baseline scenario assumes the following considerations:

a) Tbilisi

- There is no population growth during the POA. This consideration is made to evaluate what is the reliability of the system under current conditions
- It consider the current water use per capita, 368.4 liters per day per person (lpd/person). This water use per capita is fixed throughout the POA

b) Agriculture

- Table 17 shows the water demands for irrigation districts that are considered for the Baseline scenario, as well as the specific years when these demands become active and the percentage of water losses for each respective irrigation district

Table 17 Irrigation Districts considered in the Baseline Scenario

	Starting Year	Water Demand (mcm)	Conveyance Losses (%)
Saguramo	2018	1.194	50.25
Misaktsieli	2018	93.32	24.79
Aragvispiri	2019	1.39	0
Bulachauri	2018	0.83	0
Narekvavi	2019	2.18	0
Bagitchali	2025	4.3	0

c) Hydropower

- Table 18 shows the water and energy demands considered for the Baseline scenario. Monthly water demands are fixed throughout the POA; however, the energy generated will depend on the reservoir height at that specific month when the hydropower release occurs. The electricity shown in table # is only an estimation of the electricity generated if the reservoir were at the average elevation for that respective month.

Table 18 Water and electricity demands for the Baseline scenario

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
m^3/s	38.78	38.01	41.85	45.36	51.35	49.85	43.33	39.31	35.92	34.67	37.97	37.46
million m^3/month	103.9	92.0	112.1	117.6	137.5	129.2	116.1	105.3	93.1	92.9	98.4	100.3
Million kW/hour	32.6	27.2	31.1	31.8	40.5	42.3	39.9	36.6	32.1	31.6	32.9	32.7

d) Priorities

- Table 19 shows the priorities assigned to the different types of water users for the Baseline scenario. The priorities represent the order in which water will be allocated, the higher the priority, the smaller the value. For instance, water demands with a priority value of 1 will receive water before priorities with higher value. In case of shortage, water demands are curtailed by the same percentage of their water demand. In addition, water sources may have a priority assigned, meaning that water demands with higher priority (smaller values) can withdraw water from these water sources, while water demands with lower priority (higher value) cannot withdraw water from this water source.

Table 19 Priorities

	Priority
Urban & Domestic	1
Hydropower	3
Sanitary	2
Jinvali Reservoir	4
Bodorna Reservoir	5
Agriculture	6
Other Below Jinvali	7
Other Above Jinvali	7

4.4. RESULTS FROM SCENARIOS

This section shows the results of a combination:

a) Population growth rate for Tbilisi, from 0% which represents about 1.13 million inhabitants fixed throughout the POA, to 2.5% growth increase which represent an initial population of 1.13 million inhabitants to 2.57 million inhabitants by 2050.

b) Different levels of hydropower generation with respect to the current electricity generation (100% of current hydropower generation equals to 411.3 Million Kw-h per year), from no generation (0% of current) to 175% of current generation (1.75 X 411.3 = 719.7 Million Kw-h per year) in 25% increments.

In addition, these results were obtained by using the historic reservoir inflows to Jinvali reservoir from 1987 to 2016, this historic timeseries data was repeated in the period of analysis (POA) for the baseline and scenarios runs, which is 2015 to 2050.

4.4.1. TBILISI

Figure 34 and Table 20 shows the time based reliability, it shows that Tbilisi's water demand will be meet at all times (100% time-based reliability) when it occurs a combination of low population growth (≤ 0.5% per year) and low hydropower generation (≤755 of current hydropower generation). As population increases, the reliability decreases. At 1% population growth the reliability stays at 97%. This is because in the last year of the simulation (year 2050) there is not enough conveyance capacity to meet Tbilisi's water needs. As population continues to increase the time-based reliability continue decreasing. Similarly, as hydropower production increase, the period of time that Tbilisi can be fully supplied decrease. *The water supply reliability of Tbilisi is more affected by an increase in the hydropower production than by an increase in the population growth*. Under current conditions (o population growth and 100% hydropower generation) 97% of the time (34 years out of 35 years) the water demand of Tbilisi can be met, this percentage decrease more rapidly by an increase in hydropower production, than by an increase in population.

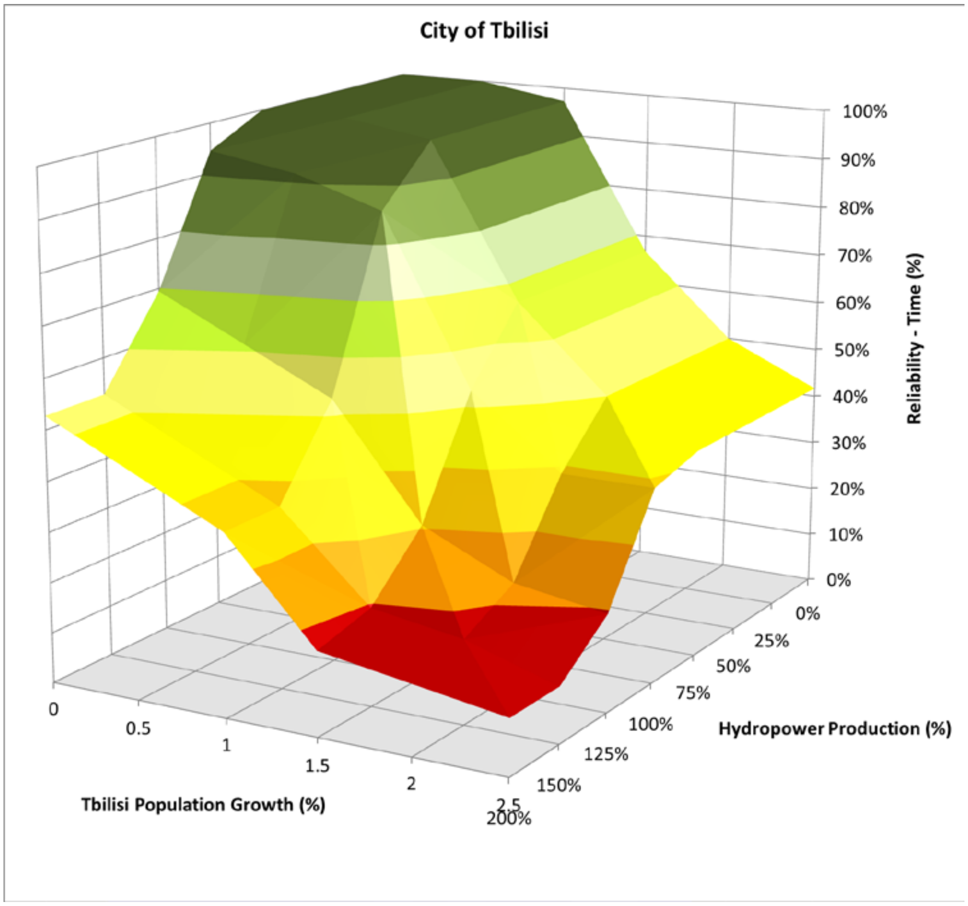


Figure 34 Time-based reliability for Tbilisi

Table 20 Time based reliability for Tbilisi.

		Reliability Time					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production (%)	0%	100%	100%	97%	67%	50%	42%
	25%	100%	100%	97%	67%	50%	42%
	50%	100%	100%	97%	67%	50%	42%
	75%	100%	100%	97%	67%	50%	42%
	100%	94%	92%	86%	53%	39%	39%
	125%	69%	61%	53%	31%	22%	19%
	150%	53%	44%	36%	19%	17%	11%
	200%	53%	44%	36%	17%	14%	11%

Results for the cities of Jinvali and Dusheti are also discussed because both cities can be affected by having a larger population (as Tbilisi does) who also is withdrawing water from their main water sources, the Aragvi River. Figure 35 and Table 21 shows the time-based reliability for the City of

Dusheti. *As the population in Tbilis increase and demand more water, the reliability of Dusheti decrease, but not as much as when the hydropower demand increases*. Notice that the time-based reliability (94%) in the current conditions (Tbilisi population growth = 0% and hydropower generation = 100%) is 94%, meaning that in 2 years out of 35, the city of Dusheti will experience a water supply deficit. Figure 36 and Table 22 show similar results for the City of Jinvali.

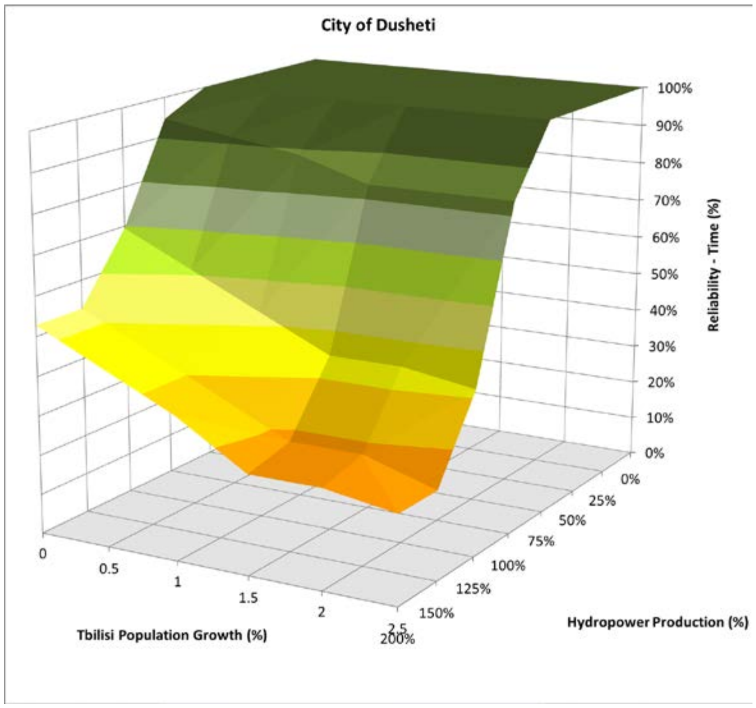


Figure 35 Time-based reliability for the City of Dusheti.

Table 21 Time-based reliability for the City of Dusheti.

		Reliability Time					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production (%)	0%	100%	100%	100%	100%	100%	100%
	25%	100%	100%	100%	100%	100%	100%
	50%	100%	100%	100%	100%	100%	100%
	75%	100%	100%	100%	100%	100%	100%
	100%	94%	92%	89%	83%	83%	83%
	125%	69%	61%	53%	44%	44%	42%
	150%	53%	44%	36%	28%	28%	22%
	200%	53%	44%	36%	25%	25%	22%

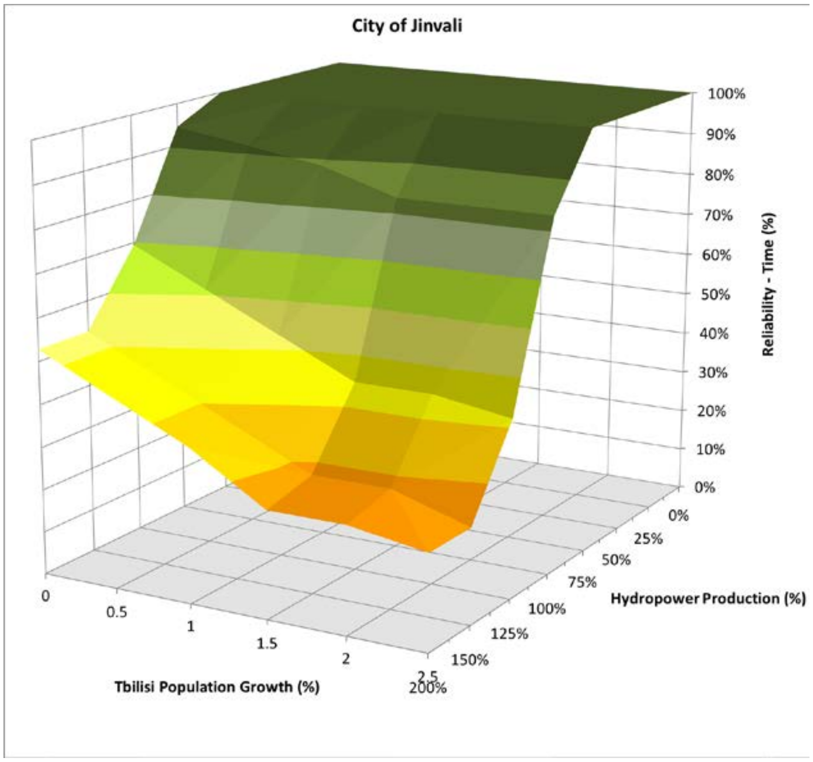


Figure 36 Time-based reliability for the City of Jinvali

Table 22 Time-based reliability for the City of Jinvali

		Reliability Time					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production (%)	0%	100%	100%	100%	100%	100%	100%
	25%	100%	100%	100%	100%	100%	100%
	50%	100%	100%	100%	100%	100%	100%
	75%	100%	100%	100%	100%	100%	100%
	100%	94%	92%	89%	83%	83%	83%
	125%	69%	61%	53%	44%	44%	42%
	150%	53%	44%	36%	28%	28%	22%
	200%	53%	44%	36%	25%	25%	22%

Figure 37 and Table 23 shows the volumetric-based reliability for Tibilisi. This performance criterion expresses the volume of water that was supplied during the entire POA in comparison with the overall water demand. In general, results show that a high volume of water is delivered over the POA in all cases. The majority of the scenarios have the volume reliability residing in the 90% range. It is only with both high population growth (2.5%) and high hydropower production (200%) that the reliability falters to the 80% range. Results show that the volume that can be supplied to Tbilisi decrease as population increase, as well as hydropower demand increase. *The amount of water that* *can be supplied to Tbilisi is more affected by an increase in the population demand than by the increase in hydropower*, this is because the City of Tbilisi has higher priority than the hydropower production.

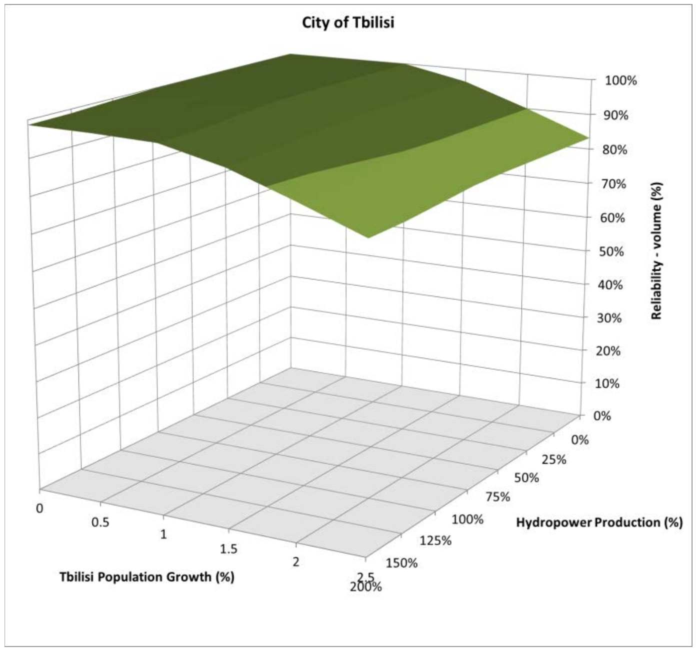


Figure 37 Volume-based reliability for the City of Tbilisi

Table 23 Volume-based reliability for the City of Tbilisi

		Reliability Volume					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production (%)	0%	100%	100%	99.97%	96%	90%	83%
	25%	100%	100%	99.97%	96%	90%	83%
	50%	100%	100%	99.97%	96%	90%	83%
	75%	100%	100%	99.97%	96%	90%	83%
	100%	99.88%	99.88%	99.81%	96%	90%	83%
	125%	99%	99%	99%	95%	89%	82%
	150%	99%	99%	98%	94%	88%	81%
	200%	99%	98%	98%	94%	87%	80%

Figure 38 and Table 24 shows the results of Vulnerability for Tbilisi (note that the z-axis has been inverted). The criterion of vulnerability expresses the severity of the deficit when they happen as its average value. For Tbilisi, the lowest vulnerability values occur when population growth is <1%. The highest instances of vulnerability occur when population growth is around 2.5%, regardless of hydropower. Again, *as the population increase the vulnerability (average deficit) increases in higher value than with an increase in hydropower production*.

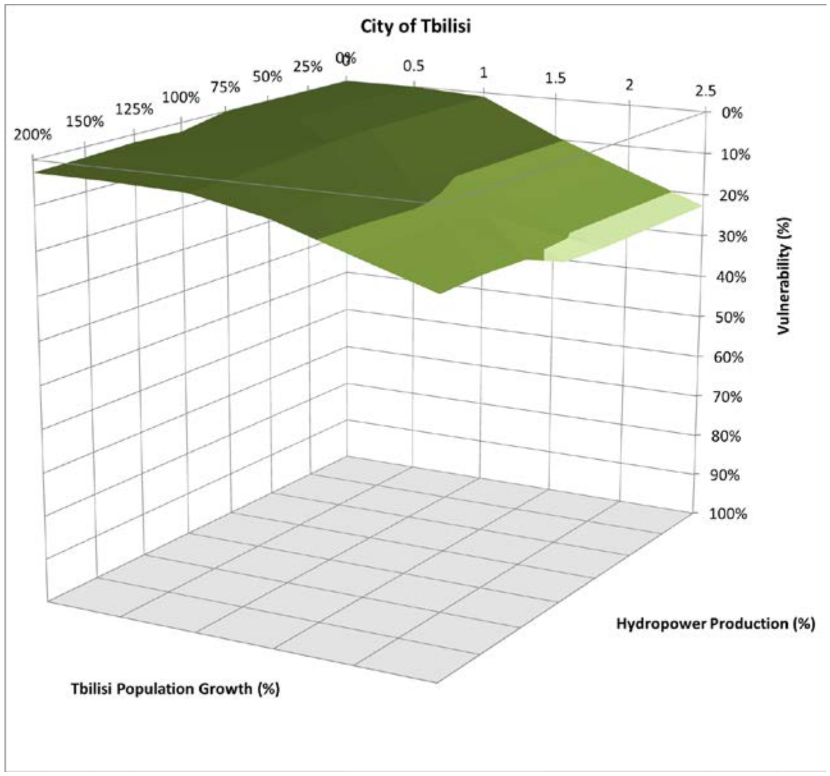


Figure 38 Water Supply Vulnerability for Tbilisi

Table 24 Water Supply Vulnerability for Tbilisi

		Vulnerability					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production (%)	0%	0%	0%	1%	9%	16%	23%
	25%	0%	0%	1%	9%	16%	23%
	50%	0%	0%	1%	9%	16%	23%
	75%	0%	0%	1%	9%	16%	23%
	100%	2%	2%	1%	7%	14%	22%
	125%	2%	2%	2%	6%	12%	18%
	150%	2%	2%	3%	7%	12%	18%
	200%	3%	3%	3%	7%	12%	18%

Figure 39 and Table 25 shows the results of the maximum deficit experienced in the POA. For Tbilisi, the max deficit is 42%, or in other words, at most 42% of Tbilisi's water demand will be left unmet. This percentage occurs when population growth is at 2.5% and hydropower use is ≥125%. For Tbilisi, the maximum deficit is influenced by both population growth and hydropower production. Similarly as with the vulnerability criterion, *as the population increases the maximum deficit increases at a higher rate with respect to an increase in hydropower production.*

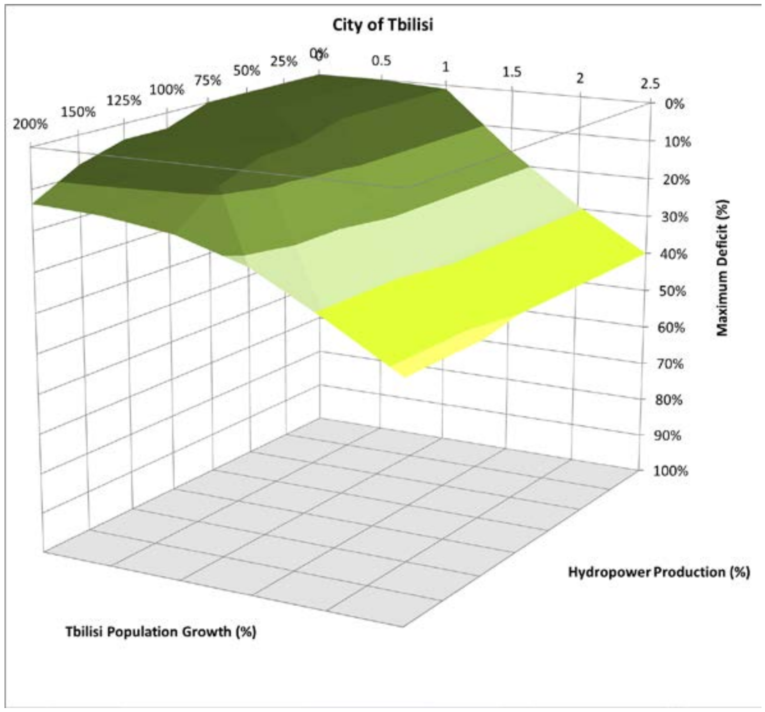


Figure 39 Maximum deficit for Tbilisi during the POA

Table 25 Maximum deficit for Tbilisi during the POA

		Maximum Deficit					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production (%)	0%	0%	0%	1%	16%	29%	40%
	25%	0%	0%	1%	16%	29%	40%
	50%	0%	0%	1%	16%	29%	40%
	75%	0%	0%	1%	16%	29%	40%
	100%	4%	4%	4%	16%	29%	40%
	125%	4%	4%	5%	19%	31%	42%
	150%	7%	8%	8%	19%	31%	42%
	200%	13%	14%	17%	22%	31%	42%

Figure 40 and Table 26 shows the water supply resilience for the city of Tbilisi. The resilience criterion expresses how fast (in terms of probability) the water supply system can come back to fully supply a water demand once a water supply deficit has occurred. For reference, the higher the percentage, the more likely a city will recover from a water deficit. For Tbilisi, the water supply will recover 100% of the time when population growth is between 0-0.5% and hydropower production is ≤100%. Once population growth exceeds 0.5% and a water deficit occurs, there is a 0% chance that the full water demand can be supplied. This occurs when Tbilisi has a high growth rate and as a consequence a high water demand that exceeds the conveyance carrying capacity of water that can be supplied through the different diversion Systems (Jinvali-Bodorna, Saguramo, Mukhrani and Natakhtari). Resilience decrease as population increase quite abruptly. At 1% growth increase rate the resilience falls to 0%, this is because the conveyance capacity has been reached and there is no more capacity to supply Tbilisi's water demand. In contrast, as hydropower production increase there is a decrease in resilience, but not as dramatic as with the increase in population growth.

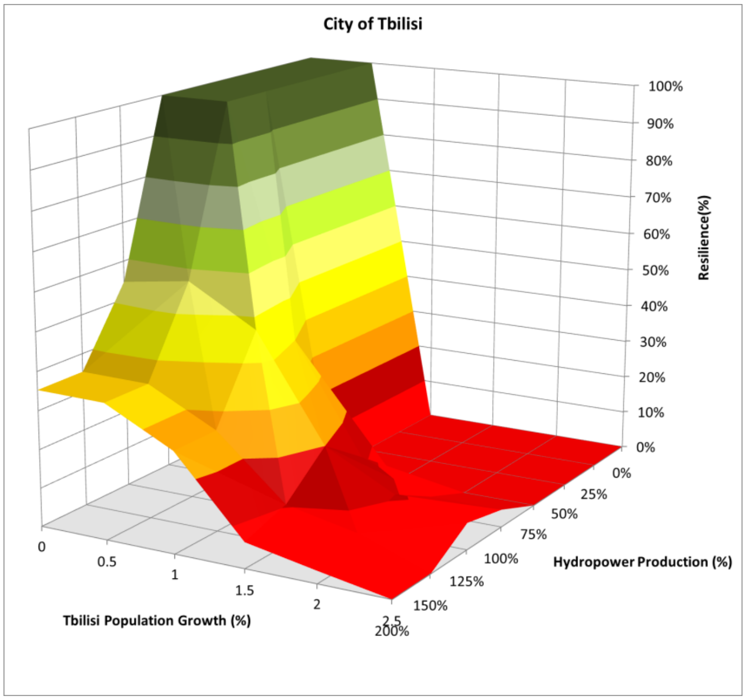


Figure 40 Water supply resilience for Tbilisi

Table 26 Water supply resilience for Tbilisi

		Resilience					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production (%)	0%	100%	100%	0%	0%	0%	0%
	25%	100%	100%	0%	0%	0%	0%
	50%	100%	100%	0%	0%	0%	0%
	75%	100%	100%	0%	0%	0%	0%
	100%	100%	100%	40%	12%	5%	5%
	125%	55%	57%	47%	20%	11%	7%
	150%	35%	35%	26%	10%	7%	0%
	200%	35%	35%	26%	7%	3%	0%

4.4.2. HYDROPOWER

Figure 41 and Table 27 shows the average annual hydropower production for Jinvali Reservoir. Results show that as the hydropower production target increase, so the hydropower production, peaking. The average annual hydropower production peaks at 125%.

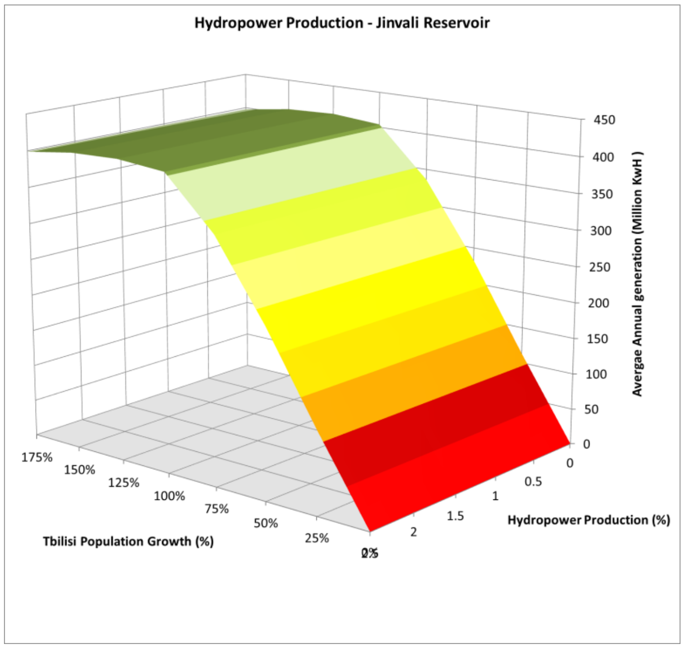


Figure 41 Average annual Hydropower production for Jinvali reservoir

Table 27 Average annual Hydropower production for Jinvali reservoir

		Average Annual Hydropower Production					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production	0%	0.00	0.00	0.00	0.00	0.00	0.00
	25%	113.24	113.14	113.01	112.89	112.83	112.79
	50%	232.18	232.16	232.00	231.82	231.72	231.65
	75%	335.51	335.51	335.51	335.51	335.51	335.51
	100%	404.09	404.12	404.16	404.23	404.28	404.29
	125%	409.73	409.88	410.08	410.25	410.31	410.37
	150%	407.12	407.34	407.61	407.83	407.94	408.03
	175%	397.62	397.91	398.25	398.50	398.64	398.79

Figure 42 and Table 28 shows the time based reliability for the hydropower production at Jinvali reservoir, they show that hydropower production will be meet at all times (100% time-based reliability) when the hydropower production target is set equal or less than 75% regardless of the population growth. *__The water supply reliability of Hydropower production in Jinvali reservoir is only affected the hydropower production target; it is not affected by an increase in the population growth__*. The months of the year that suffer a significant decrease in the time-based reliability are October to March. Under current conditions (0% population growth and 100% hydropower generation) 93% of the time (33 years out of 35 years) the hydropower production target for Jinvali reservoir can be met. This percentage decreases rapidly when the hydropower production target is increased.

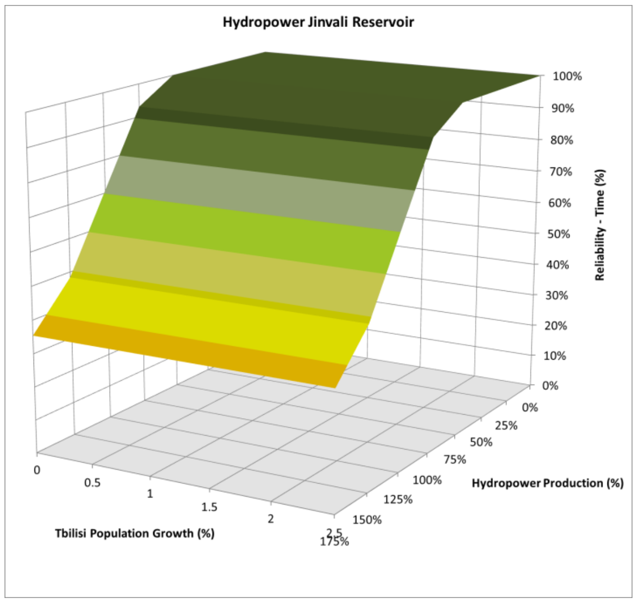


Figure 42 Time-based reliability for hydropower production in Jinvali reservoir

Table 28 Time based reliability for hydropower production of Jinvali reservoir.

		Reliability - Time					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production	0%	100%	100%	100%	100%	100%	100%
	25%	100%	100%	100%	100%	100%	100%
	50%	100%	100%	100%	100%	100%	100%
	75%	100%	100%	100%	100%	100%	100%
	100%	93%	93%	93%	93%	93%	93%
	125%	71%	71%	71%	71%	71%	71%
	150%	48%	48%	48%	48%	48%	48%
	175%	35%	35%	35%	35%	35%	35%

Figure 43 and Table 29 shows the volumetric-based reliability for hydropower production in Jinvali reservoir. In general, the volume that can be diverted for hydropower production decrease rapidly with higher hydropower production targets. Results show that hydropower generation is not sensitive to increases in population, this is because of the climate seasonality, during wet months there is enough water to produce energy, while during dry months there is simply no water to produce electricity. *<u>The amount of water that can be passed through the turbines is only affected by an increase in hydropower production.</u>*

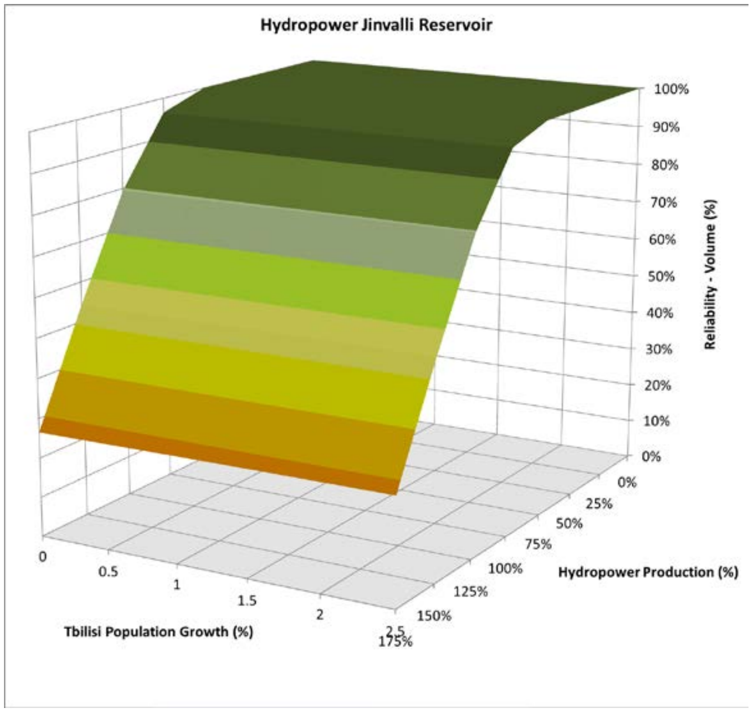


Figure 43 Volume-based reliability for hydropower production in Jinvali

Table 29 Volume-based reliability for hydropower production in Jinvali

		Reliability - Volume					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production	0%	100%	100%	100%	100%	100%	100%
	25%	100%	100%	100%	100%	100%	100%
	50%	100%	100%	100%	100%	100%	100%
	75%	100%	100%	100%	100%	100%	100%
	100%	96%	96%	96%	96%	96%	96%
	125%	79%	79%	80%	80%	80%	80%
	150%	54%	54%	54%	54%	54%	54%
	175%	27%	27%	27%	27%	27%	27%

Figure 44 and Table 30 shows the results of Vulnerability for Tbilisi (note that the z-axis has been inverted). The criterion of vulnerability expresses the severity of the deficit when they happen as its average value. For hydropower generation, there is abrupt increase in vulnerability (average deficit) when the hydropower production target is above 75%. Similarly, *<u>the vulnerability of hydropower production is dependent on the hydropower production target</u>*.

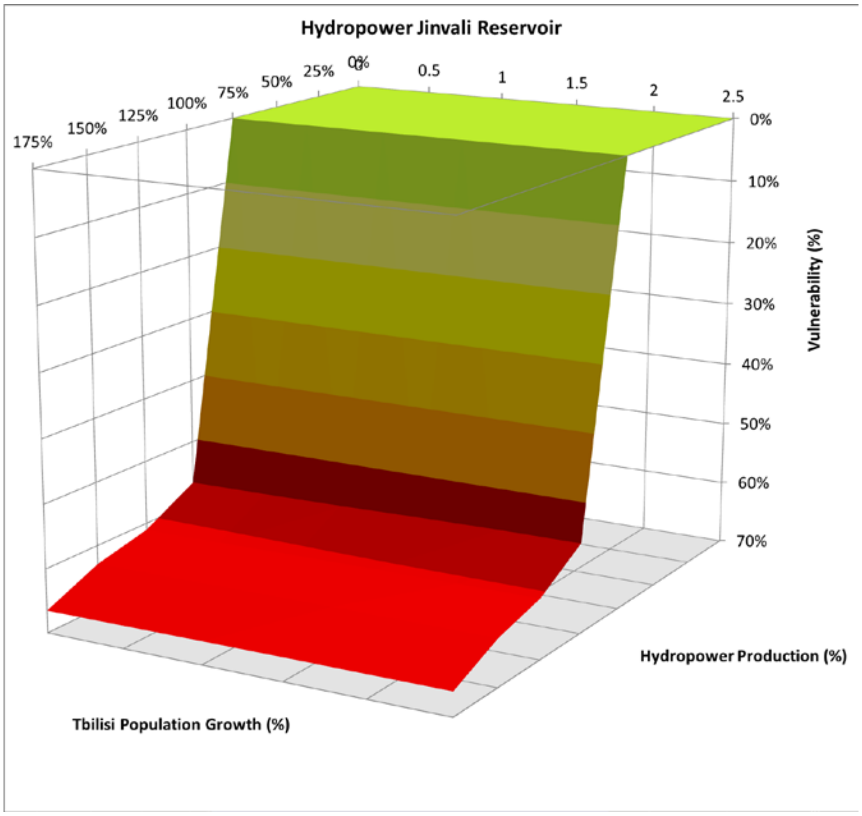


Figure 44 Water Supply Vulnerability for hydropower production at Jinvali reservoir

Table 30 Water Supply Vulnerability for hydropower production at Jinvali reservoir

		Vulnerability					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production	0%	0%	0%	0%	0%	0%	0%
	25%	0%	0%	0%	0%	0%	0%
	50%	0%	0%	0%	0%	0%	0%
	75%	0%	0%	0%	0%	0%	0%
	100%	57%	57%	56%	56%	56%	56%
	125%	61%	61%	61%	61%	61%	61%
	150%	63%	63%	63%	63%	63%	63%
	175%	67%	66%	66%	66%	66%	66%

Figure 45 and Table 31 shows the results of the maximum deficit experienced in the POA. For hydropower production in Jinvali reservoir, the max deficit is 100%, or in other words, there will be months when no hydropower production may occur. This percentage occurs when the hydropower production target is set to 100% (as it is currently) or higher. Similarly as with the previous performance criteria, *as the water production target increases the maximum deficit also increases.*

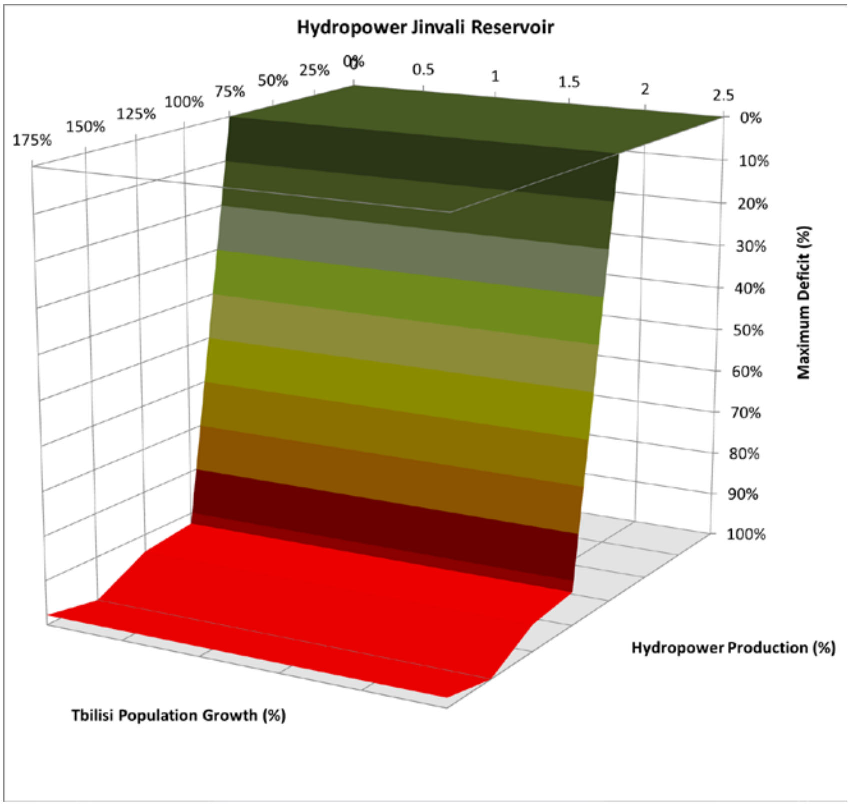


Figure 45 Maximum deficit for hydropower production in Jinvali reservoir

Table 31 Maximum deficit for hydropower production in Jinvali reservoir

		Maximum Deficit					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production	0%	0%	0%	0%	0%	0%	0%
	25%	0%	0%	0%	0%	0%	0%
	50%	0%	0%	0%	0%	0%	0%
	75%	0%	0%	0%	0%	0%	0%
	100%	92%	92%	92%	92%	92%	92%
	125%	94%	94%	94%	94%	94%	94%
	150%	100%	100%	100%	100%	100%	100%
	175%	98%	98%	98%	98%	98%	98%

Figure 46 and Table 32 shows the water supply resilience for hydropower production in Jinvali reservoir. For hydropower production, the water supply will recover 100% of the hydropower production target is equal or less than 75% of the current hydropower diversion. Once the hydropower production target exceed this percentage (≤100%); the capacity of the system to recover from deficits drop drastically to 33% or less. Similarly as with the previous performance criteria, *as the water production target increases the resilience of the system decrease.*

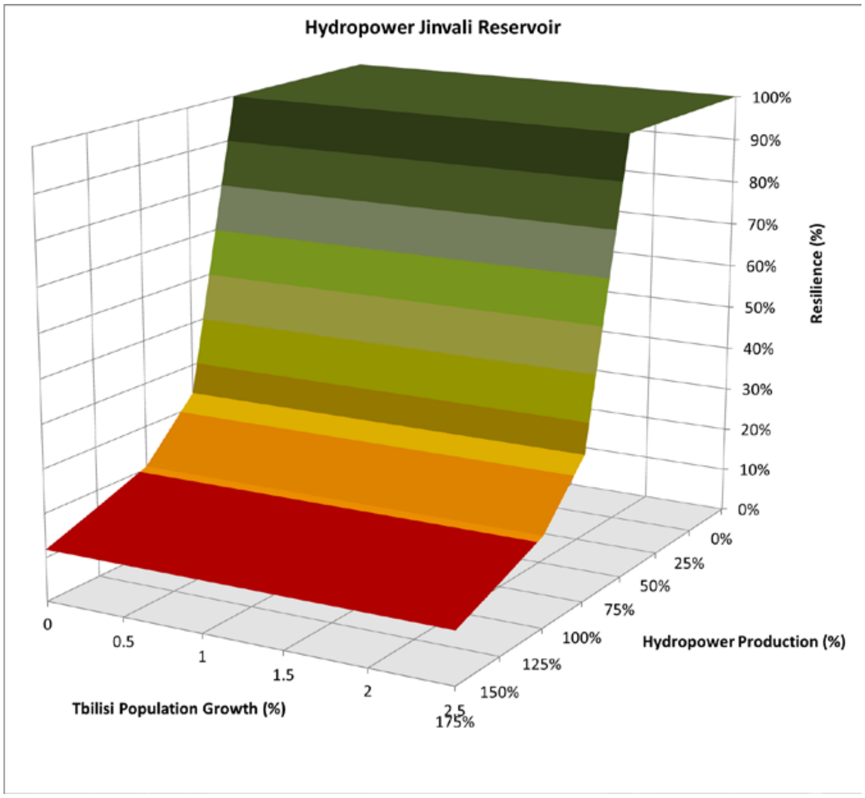


Figure 46 Water supply resilience for hydropower production in Jinvali reservoir

Table 32 Water supply resilience for hydropower production in Jinvali reservoir

		Resilience					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production	0%	100%	100%	100%	100%	100%	100%
	25%	100%	100%	100%	100%	100%	100%
	50%	100%	100%	100%	100%	100%	100%
	75%	100%	100%	100%	100%	100%	100%
	100%	33%	33%	33%	33%	33%	33%
	125%	21%	21%	21%	21%	21%	21%
	150%	16%	16%	16%	16%	16%	16%
	175%	12%	12%	12%	12%	12%	12%

4.4.3. AGRICULTURE

Figure 47 and Table 33 show the time-based reliability for agriculture water demands (Saguramo, Lami-Misaktsieli, Bulachauri, Aragvispiri and Bagitchali Irrigation districts) downstream of Jinvali reservoir. Results show that water supply for irrigation districts depend on both, hydropower production target and population growth. In general, as population increases, the water supply reliability decreases because less water is available. In contrast, the water supply reliability is around 80% when there hydropower production target is equal or less than 50%. This means that there is not enough water that was release for hydropower generation that is left in the system to be taken by irrigation districts. The time-based reliability is 100% when the hydropower production is set at 75% and 100%. At this level of hydropower production, there is enough water left to be taken by the irrigation districts. When the hydropower production increases to 125%, then, irrigation districts start suffering again because there is not enough water stored in the reservoir during drought periods and water shortages resume.

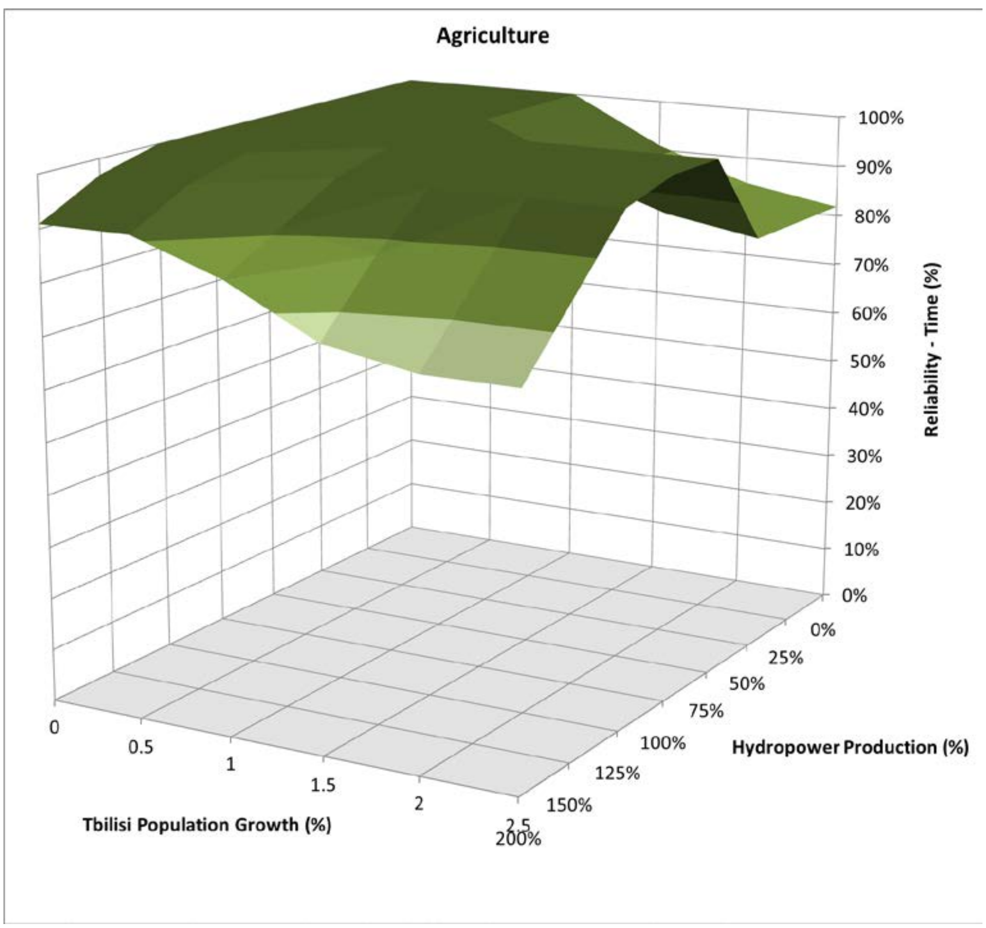


Figure 47 Time-based reliability for Agriculture demands

Table 33 Time-based reliability for Agriculture demands

		Reliability Time					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production	0%	100%	100%	100%	91%	85%	82%
	25%	100%	100%	100%	91%	85%	82%
	50%	100%	100%	100%	91%	85%	82%
	75%	100%	100%	100%	100%	100%	100%
	100%	100%	100%	100%	100%	100%	100%
	125%	100%	100%	97%	97%	97%	97%
	150%	97%	97%	91%	88%	85%	85%
	200%	91%	91%	85%	76%	73%	73%

In terms of volumetric reliability (Figure 48), the overall water supply for irrigation districts is quite high, at least 98% of the total volume requested or higher, as shown in Table 34

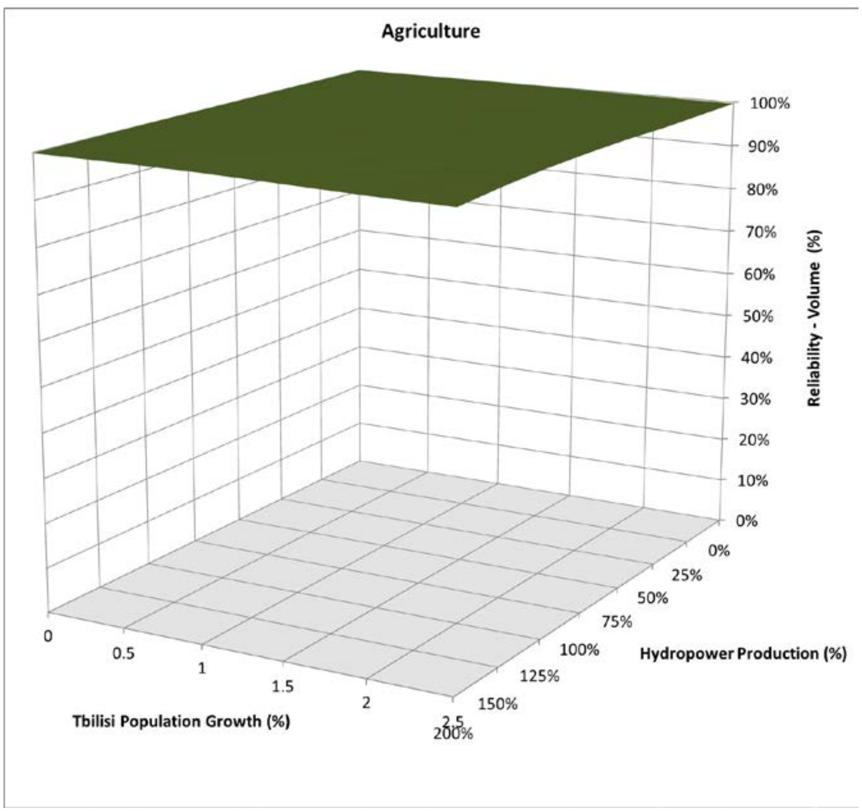


Figure 48 Volumetric reliability for Irrigation Districts below Jinvali reservoir

Table 34 Volumetric reliability for Irrigation Districts below Jinvali reservoir

		Reliability - Volume					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production	0%	100%	100%	100%	99.9%	99.8%	99.7%
	25%	100%	100%	100%	99.9%	99.8%	99.7%
	50%	100%	100%	100%	99.9%	99.8%	99.7%
	75%	100%	100%	100%	100%	100%	100%
	100%	100%	100%	100%	100%	100%	100%
	125%	100%	100%	99.9%	99.8%	99.8%	99.8%
	150%	100.0%	100.0%	99.9%	99.6%	99.4%	99.3%
	200%	99.8%	99.8%	99.6%	99.2%	98.7%	98.4%

5. CONCLUSIONS

This report documents the data inputs and key parameters for the construction of the Aragvi River system, the model has been calibrated and tested to verify its adequate performance. The Aragvi model has been used by the project team members to evaluate the impact of several scenarios that consider different population growths for Tbilisi, as well as hydropower production targets.

Model Development

The model has three main screen views: Schematic, Data, and Results. This report looks at the Data screen view in detail, including the three main branches: Key Assumptions, Demand Sites and Supply and Resources. There are 25 demand sites in the model, representing withdrawals for municipalities, agriculture, and other, with a total annual water use of 831.246 mcm (334.946 of consumptive use). These demand sites are managed by several variables declared in Key Assumptions and the Supply and Resources. The main sources of water for these demand sites are reservoirs and headflows for each tributary. The other source of water is groundwater which provides additional water for this region but are not considered in this model. The data entered for all of these parameters have been provided from multiple sources and some data still need to be entered for the model to increase its usage and performance. However, the present stage of the model demonstrates the current strain on the system and the need to manage these resources for optimal conservation.

In addition a model interface was developed in Excel® with the objective to provide a tool that can be used by different scientists, engineers and decision makers interested in exploring how the Aragvi river basin may respond to different water management strategies.

Model Testing

The model testing phase reported here for the reservoir storage demonstrates that for the hydrologic period of analysis from Jan/1987 to Dec/2016 modeled storage values in Jinvali reservoirs compared with historical storages has a high correlation coefficients greater than 0.94. Additionally, comparison of modeled and historical hydropower in the basin shows correlation coefficients higher than 0.83. On the overall, the model is behaving very similar to the real system; however, there are opportunities for improvements in the model.

Evaluation of Water Management Strategies

A combination of several population growth rates (from 0% to 2.5%) and hydropower production targets (from 0% to 200%) were evaluated an analyzed. The water supply for Tbilisi depends on both, its own population growth rate and the hydropower production targets set in Jinvali reservoir. The population growth plays an important role in the last years of the simulation runs (year 2040 and beyond), when the conveyance capacity of the system reaches its maximum capacity and no more water can be transported to supply the water demand of Tbilisi; the higher the population growth, the lower the water supply reliability. In addition, as the hydropower production target increase, the water supply for Tbilisi becomes less reliable because less water is left stored in Jinvali reservoir. The water supply for Tbilisi is more vulnerable to increases in hydropower production than in population increase. Currently, Tbilisi has a water supply reliability of 97%, which means that a water deficit can happen in one out of 35 years. Population increase and climate change can play a significant role to reduce the water supply reliability for Tbilisi.

Hydropower production in Jinvali reservoir depends more on the hydropower production target that is set throughout the POA than the population growth of Tbilisi. The hydropower production peaks at 125% of the current hydropower production target. However, this high production target may negatively affect the water supply reliability of other water users, such as Tbilisi. The water supply reliability of hydropower is severely reduces as the hydropower production target increased.

Agriculture demands (Saguramo, Lami-Misaktsieli, Bulachauri, Aragvispiri and Bagitchali Irrigation districts) depends on both, population growth rate and hydropower production targets. At low hydropower production the small irrigation districts experience water supply deficits because there is not enough water passed through the turbines and left in the Aragvi River, so irrigation districts can divert that water. When the hydropower production target is set at 75% or 100%, the water supply reliability for irrigation districts is optimal, they receive their full water demand at all times regardless any other variable, including the population growth rate of Tbilisi. Once the hydropower production target is increased above 125%, then irrigation districts start experiencing deficits again because of lower reservoir storages during dry months. The population growth rate of Tbilisi affects the water supply reliability of the irrigation districts, but not as much as the hydropower production target.

REFERENCES

GEOSTAT, 2016. 2014 General Population Census.
Yates, D., Sieber, J., Purkey, D., Hubert-Lee, A., 2005. WEAP21-A Demand-, Priority-, and Preference-Driven Water Planning Model. Part 1: Model Characteristics. Water International, 30(4): 487-500.