sustainability

Article

Multi-Objective Water Planning in a Poor Water Data Region: Aragvi River Basin

Samuel Sandoval-Solis [1,*], J. Pablo Ortiz-Partida [2] and Lindsay Floyd [1]

1 Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA; llfloyd@ucdavis.edu
2 Climate and Energy Program, Union of Concerned Scientists, Oakland, CA 94607, USA; jportiz@ucsusa.org
* Correspondence: samsandoval@ucdavis.edu

Abstract: Water resources planning in regions with sufficient data continuity and quality is complex, but in regions with poor water data, the task is further complicated. In this paper, we share our experience developing a multi-objective technical assessment of water resources in a region with scarce water data. This research is an example of collaborative modeling in which stakeholders were involved during the modeling process to create a model using the Shared Vision collaborative strategy for water planning in the Aragvi River Basin in the country of Georgia. We developed a regional water planning model suitable for evaluating water supply and water demand interaction as well as current and alternative water management strategies. Remarks from scenario development enlightened the need for water efficiency and conservation activities as currently the system is not entirely reliable, and its reliability is expected to decline with population growth and increased hydropower demands. This research is a strong foundation for future water-related projects in the region.

Keywords: water management; water allocation model; collaborative modeling; stakeholder involvement; Caucasus Region; shared vision; WEAP

Citation: Sandoval-Solis, S.; Ortiz-Partida, J.P.; Floyd, L. Multi-Objective Water Planning in a Poor Water Data Region: Aragvi River Basin. *Sustainability* **2022**, *14*, 3649. https://doi.org/10.3390/su14063649

Academic Editor: Mashor Housh

Received: 26 December 2021
Accepted: 17 March 2022
Published: 20 March 2022

1. Introduction

Computational water models are an effective way to quantify interactions and predict the current and future water demands of a watershed system, with a relatively accurate approximation when continuous and reliable data is available. Models can be utilized in the planning field, as they provide a diverse array of information, especially data pertaining to water supply and demands, environmental flows, historic records, and nuanced political demands of water users. Planners or policymakers may find computational water models especially useful when deciding how to best implement policies and serve the needs of human and environmental systems alike. An important part of modeling success and model implementation is the consideration of stakeholders during the modeling process in a way that allows their inquiries to be integrated within the model, so that they gain confidence in the model's accuracy by understanding its processes [1]. Stakeholder inclusion also helps to develop a shared vision of the basin in which common goals are identified to ease negotiation processes.

Our comprehensive model of the Aragvi River Basin provides information relevant to planning for an unpredictable future. By having a model that is easily manipulated to reflect changing variables such as population growth rates or water demands, stakeholders can more accurately plan for non-linear environmental and anthropogenic changes. Some models used in planning fail to account for the unpredictability of the environment, leading to management approaches that are insufficient in the event of abrupt changes [2]. The Aragvi River Basin Model considers economic and domestic changes and reflects a multitude of scenarios that could impact future water availability in Tbilisi, the capital of the county of Georgia.

The process of creating the model and presenting to a diverse array of stakeholders would provide tools for transformational change planning [2]. Collaborative modeling is a general definition for the act of including technical and conciliatory skills that consider a participatory process to manage water resources in an efficient manner [1]. The act of engaging the public and pertinent stakeholders in collaborative modeling provides the opportunity for enhanced learning regarding the system being computed, and this approach has subsequently been gaining increasing support and attention. Water management is a nuanced field and creating a competent understanding of the system is vital for effective governance [3]. Collaborative modeling when coupled with participatory processes leads to informed decisions regarding natural resource management [1]. Similarly, Shared Vision Planning is a modern approach that utilizes traditional planning techniques, computer modeling, and structured public participation to create a comprehensive approach for effective water management [1,4]. Conflicts in water management may arise for any number of reasons, especially when water rights are at stake. Utilizing a Shared Vision Planning approach where stakeholders are well informed on the system and there is confidence in the model's validity and transparency may help alleviate potential conflicts. This was demonstrated in a study wherein three of five study areas successfully applied a shared vision process for drought preparedness, reporting that it helped with effective communication, transparency, reaching consensus, and creating a process for conflict resolution [4]. Another case that explored the use of integrated water resource modeling with participatory governance in four different international watersheds found that with the collaborative modeling approach, there was an increase in both systemic learning and solution complexity [5]. Stakeholder involvement is a vital component of the Shared Vision Planning, especially for accurate learning regarding the watershed, but when the issues are considered too trivial or are not clearly understood, then eliciting this participation can pose a challenge to the collaborative modeling approach [6]. The same study also emphasizes the importance of scientific trust and neutrality to best implement clear collaborative modeling.

The overall objective of this research is to develop a multi-objective (agriculture water supply, hydropower, urban water supply, environment, and recreation) technical assessment of water resources in the Aragvi River Basin, which is the main water source for Tbilisi, capital of Georgia. This project was conducted in cooperation with the United States Agency for International Development (USAID) Government for Growth in Georgia (G4G) project, 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 balancing needs between competing water uses, and a major challenge is adapting the infrastructure and allocation policies to prepare for predicted water demands increases. The specific objectives of the study are as follows: (i) develop a water planning allocation model and evaluate current and alternative water management strategies for the Aragvi River Basin; (ii) interact and coordinate with the Ministry of Environment and Natural Resources Protection (MoENRP) and other stakeholders to ensure agreement on model scenarios; and (iii) build technical capacities within the GoG in water resources modeling.

This study aims to create a comprehensive planning model of future water supply and demand in the Aragvi River Basin that can be utilized by city and environmental planners as well as Georgian policymakers. Within the following sections, we present as a case of study the Aragvi River Basin, the development of the water allocation model, the selection and evaluation of scenarios, and discussion of current water policies and potential problems that currently pose a threat to Tbilisi's water supply.

2. Case Study: Aragvi River Basin, Georgia

The Aragvi River Basin, located in the northeast part of Georgia, belongs to the Mtkvari (Kura) River Basin (Figure 1). The length of the Aragvi river is about 122 km, and the catchment area is around 2700 km^2. Administratively, the basin is 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 other water uses such as hydropower generation and irrigation draw from the same water source. In 2015, the total water use was estimated to be 2093.124 million m^3, from which 1408.400 million m^3 corresponded to hydropower (67%), 589.096 million m^3 to urban water supply (28%), 94.025 million m^3 to agriculture (4%), and 1.603 million m^3 to industry (1%) [7]. Water used for hydropower production cannot be considered entirely as a consumptive use; for instance, in 2015, out of the 1408.400 million m^3 used for hydropower, 684.724 million m^3 were used in hydropower and were reused for other types of use (urban, agriculture and industry), while 723.676 million m^3 were released from Zhinvali reservoir exclusively for hydropower generation [7] and left the basin.

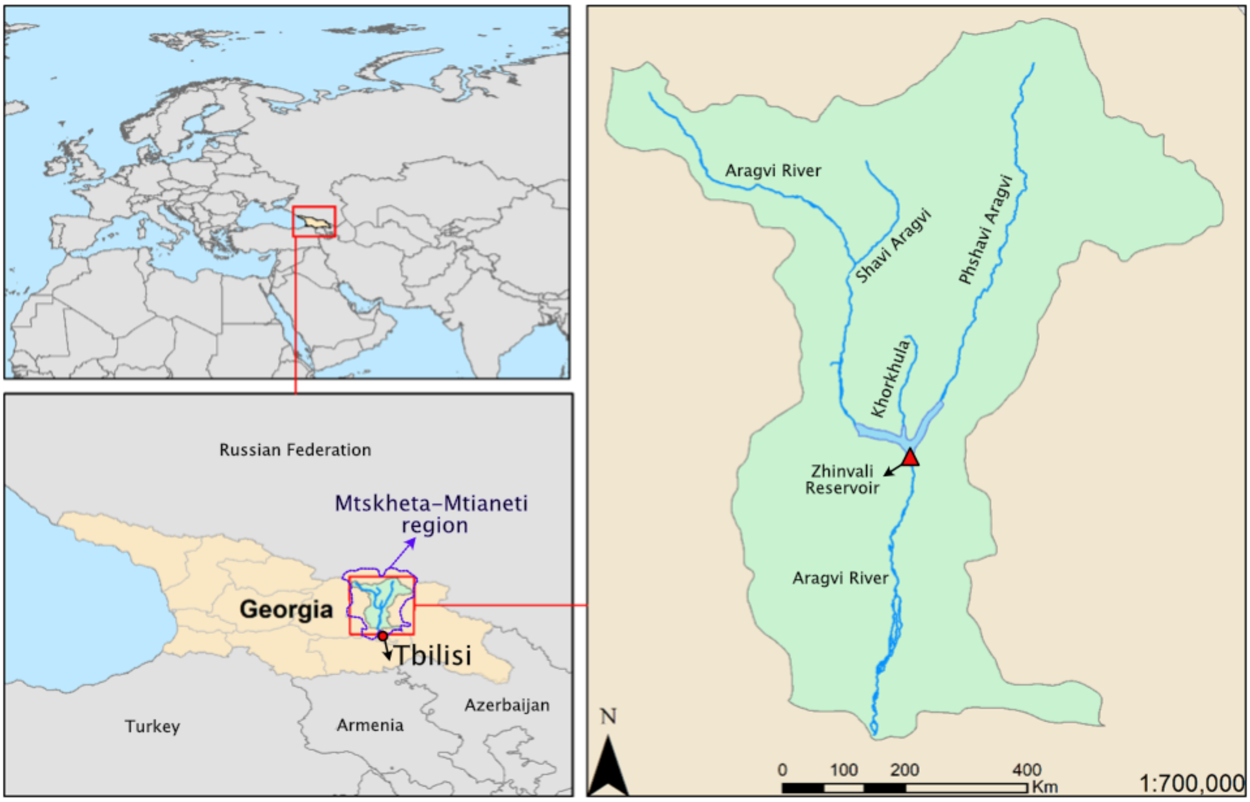

Figure 1. Main tributaries of the Aragvi River included in the WEAP Model.

Agriculture holds 40% of production value among the profiled production varieties around the Aragvi River Basin. The different agricultural sectors of the region are horticulture, livestock, beekeeping, fishing, and greenhouse management. Agricultural production in the Mtskheta-Mtianeti region in 2013 had increased by 251.3 million GEL (≈$81.5 M) compared to 2010. The output, which defines an economic entity by volume of production and the volume of products sold, consisted of 454.5 million GEL (≈$150 M) in 2013. There are two irrigation systems considered in this exercise, Lami-Misaktsieli and Saguramo, that in 2015 diverted 93.318 and 0.707 million m^3, respectively, for a total agriculture use of 94.025 million m^3 [7].

The different water-user sectors were identified based on the analysis of the socio-economic portfolio of the Mtskheta-Mtianeti region. According to the official information provided by Georgia Water and Power (GWP), drinking water for Tbilisi population is delivered primarily from the Aragvi River Basin [8]. Current total urban and rural municipal water consumption amounts to 715.89 million m^3/year, based on the population living in the Aragvi River Basin in 2016 and the city of Tbilisi. Per capita water consumption for the urban population was provided by the respective water supply companies, and per capita water consumption for the rural population was defined based on surveys and information obtained through field research [7]. The city of Tbilisi is the largest municipal water consumer in Georgia, and its total annual water demand amounts to 90% of total municipal annual water use from the Aragvi River Basin.

The climate in Aragvi River Basin is classified as arid, and therefore additional irrigation is needed for agricultural lands that grow Georgia's major crops such as wheat, corn, potatoes, tomatoes, and grapes. The majority of irrigation systems have been historically developed and operated in the Mtskheta-Mtianeti region. Current use by the agriculture sector of water from the Aragvi River Basin amounts to 10.94 million m^3/year [9], and in 2015 the total irrigated area in the Aragvi River Basin totaled 1409.6 ha. However, considering the high losses of the system (up to 50%), water consumption per ha is relatively inflated and adds up to 4500 m^3/ha. Water losses were defined based on information obtained during by the USAID G4G project field trips and interviews with representatives of the local branches of the Georgian Amelioration Department [9].

Currently, the hydropower sector is the largest water user in the country. The Aragvi River is intensively used for hydropower production, and it stands out in terms of capacity, with an annual potential capacity of 0.5 million kilowatts. Due to the river-bed inclination, the Aragvi River has high energy potential. The Aragvi River Basin is one of the premier rivers intensively used for power generation today in Georgia and is scheduled to launch more hydropower plants (HPP) in the future [10]. At present, there are two large operating HPPs in the river basin, Zhinvali HPP and Aragvi HPP, with total installed capacities of 138.5 MW and annual capacities of 447 GWh [11]. The Zhinvali HPP complex includes the Zhinvali reservoir (storage capacity of 520 million m^3) and the forebay Bodorna reservoir (storage capacity of 1 million m^3), which regulate the outflows from Zhinvali.

2.1. Aragvi Basin Planning Model

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 (SEI) [12].

The constructed Aragvi Basin Planning Model, hereafter referred to as the Aragvi Model, includes the mainstem of the Aragvi River and the main tributaries above Zhinvali Reservoir: Shavi Aragvi, Phshavi Aragvi and the Khorkhula River (Figure 1). It also integrates the Zhinvali reservoir, formed from the Zhinvali hydropower dam constructed in 1986, which is one of the largest dams in Georgia. The Zhinvali hydropower dam is 102 m tall and generates 130 MW hydro-electric power. The Zhinvali reservoir divides the basin into an upper and a lower section, modifying the hydrologic regime of the river. The majority of water resource users are located downstream of the Zhinvali reservoir, in the lower reaches of the Aragvi River. Water from the Aragvi River is used for irrigation and water supply to the city of Tbilisi and is the main source of water for local settlements and small manufactures. Water for Tbilisi is supplied by three water sources: the Aragvi River, the Mukhrani Aquifer, and the Natakhtari Aquifer. There are seven diversion points for water supply to Tbilisi: (1) a direct diversion from the Zhinvali Reservoir to Tbilisi, along the mainstem of the Aragvi River from (2) Bulachari, (3) Choporti-Misaktsieli, and (4) Saguramo to Saguramo station and from there to Tbilisi; from (5) the Mukhrani Aquifer to Tbilisi; from (6) the Natakhtari aquifer and (7) the new Natakhtari aquifer infrastructure to Tbilisi. A model schematic is presented in Figure 2.

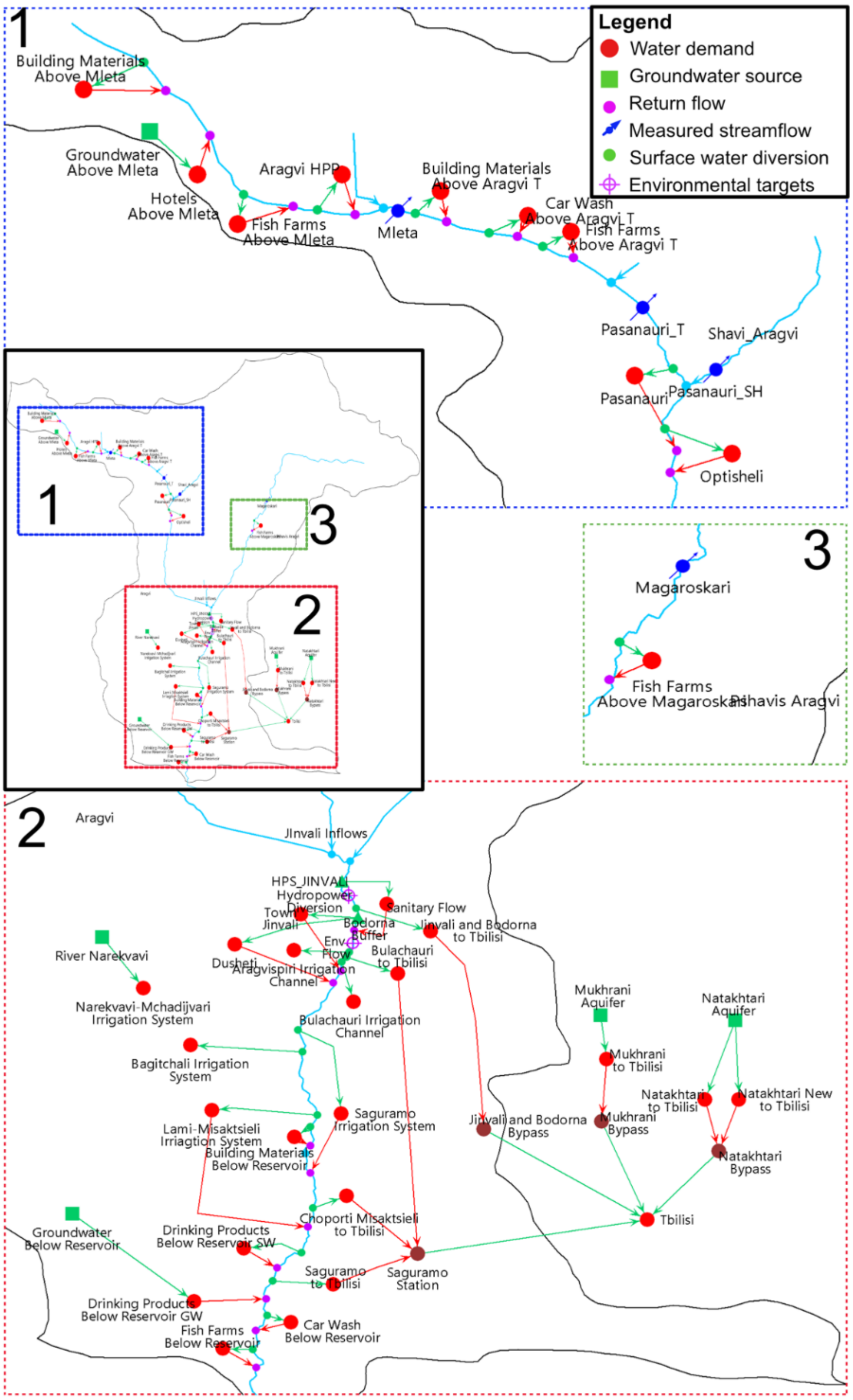

Figure 2. Model Schematic from WEAP. This schematic show only approximate location of water demands, groundwater sources, return flows, streamflow gages, and surface water diversion in the system. Note: the location of Tbilisi do not correspond with actual location which is further downstream.

Data collected from January 1960 to December 1992 from four gauges, namely Mleta, Pasanauri_T, Pasanauri_SH, and Magoroskari, serves as the basis for historical streamflow data provided by NEA and GWP, and is used to determine water management constraints due to plausible environmental factors. Multiple data sources were used to complete the data for developing the model (Table 1). Water demands from 2015 [7] were considered as baseline values for this study. Data for hydropower generation, releases, and reservoir storage was provided by GWP. All model inputs, equations, assumption and outputs are documented in the cited report [13] and publicly shared [14].

Table 1. Data sources.

Data	Sources	Model Input
Water Demands	Ministry of Environment and Natural Resources Protection (MoENRP)	Environmental water demands
	Georgia Water and Power (GWP)	Hydropower water demand
	United Water Supply Company of Georgia (UWSCG)	Tbilisi Population and consumptive water useWater users upstream of Zhinvali Reservoir
	Ministry of Agriculture/Georgian Amelioration (GAC)	Agriculture
	Ministry of Energy and National Statistics Office of Georgia	
Stream Flows	National Environmental Agency (NEA)	Environmental water demands
	Georgia Water and Power (GWP)	Water releases for hydropower
Inflows, Outflows, Reservoir Storage	Georgia Water and Power (GWP)	Streamflow data and reservoir storage

Through Visual Basic scripts, variables from Excel were run through the WEAP model, and final results were produced through Excel. The model works to directly compare a business as usual scenario with a scenario whose variables have been manipulated by the user. This allows for ease of comparison to best analyze the water demand needs of the Zhinvali reservoir, with particular efforts given to Tbilisi.

Two different flow datasets were used to compensate for the scarce streamflow data (i) the historic streamflow data from January 1960 to December 1992 for four streamflow gauges, namely Mleta, Pasanauri_T, Pasanauri_SH, and Magoroskari, provided by NEA (NEA, personal communication, 3 May 2017), and (ii) historic inflows into the Zhinvali reservoir from January 1987 to December 2016, provided by GWP. The historic streamflow data are more conservative time series data, in that the monthly and annual streamflow has less water flowing into the Zhinvali reservoir (median annual flow of 1277 million m^3/year) than the historic time series data of inflows recorded into the Zhinvali reservoir (median annual flow of 1387 million m^3/year). For this research study, the historic reservoir inflows to Zhinvali reservoir from 1987 to 2016 was defined as reference data and repeated in the period of analysis (POA) of 2015 to 2050 for the baseline and scenarios runs.

We considered the principle of mass balance on both time series. First, for the historic streamflow data from four 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 (Equation (2)).

$$\Delta S_t = I_t - O_t + IF_t \tag{1}$$

$$IF_t = O_t - I_t + S_t - S_{t-1} \tag{2}$$

For the historic inflows to the Zhinvali reservoir ($Inflows_t^{Jinvali}$), we calculated a mass balance for the inflows (I_t), outflows (O_t) and change of storage (ΔS_t) (Equation (3)) to estimate α_t, a closure term to meet the mass balance principle (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. The correction is a closing term similar to the incremental flows but for reservoir settings.

$$\Delta S_t = S_t - S_{t-1} = I_t - O_t + \alpha_t \tag{3}$$

$$\alpha_t = O_t - I_t + S_t - S_{t-1} \tag{4}$$

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

We calculated the annual water demands from Tbilisi using the average water user per capita per day (lpd/person) and the population of the city (Equation (6)). The water use per capita estimated for Tbilisi in 2016 was 368.4 lpd/person [7]. Due to the conveyance losses to supply Tbilisi from its seven water diversions (*i*), the actual water abstraction is greater than the Tbilisi water demand. There are seven diversion points for water supply to Tbilisi: (1) a direct diversion from the Zhinvali Reservoir to Tbilisi; along the mainstem of the Aragvi River from (2) Bulachari, (3) Choporti-Misaktsieli and (4) Saguramo to Saguramo station and from there to Tbilisi; from (5) the Mukhrani Aquifer to Tbilisi; from (6) the Natakhtari aquifer and (7) the new Natakhtari aquifer infrastructure to Tbilisi [7]. Equation (8) is used to determine the water abstraction from each water source.

$$Water\ Use_t^{Tbilisi}[mcm] = \frac{\frac{(Population[cap]*Ldp[L]*365)}{1000\ [L/m^3]}}{1000000} \quad (6)$$

$$Water\ Use_t^{Tbilisi}[mcm] = \sum_{i=1}^{i=7}\left[WaterAbstraction_t^i\left(1 - Conveyance\ Losses^i\right)\right] \quad (7)$$

$$Water\ Abstraction_t^i = \frac{WaterUse_t^{Tbilisi} * ShareWaterSource^i}{(1 - Conveyance\ Losses^i)} \quad (8)$$

The conveyance losses (*Conveyance Losses*^{i}) and share that each water source (*ShareWaterSources*^{i}) contributes to the total water use of Tbilisi (*Water Use*$_t^{Tbilisi}$) were obtained from Source: GWP Company, United Water Supply Company (UWSCG), Georgian Amelioration Company (GAC). Table 2 shows the conveyance losses considered for supplying Tbilisi, Saguramo, and Lami-Misaktsieli [7,13].

Table 2. Conveyance losses considered for supplying Tbilisi, Saguramo and Lami-Misaktsieli.

Water Demand	Diversion Point	Conveyance Losses (%)
Tbilisi	Jinvali Reservoir	79.99
	Bulacahri	56.35
	Choporti	56.35
	Saguramo	56.35
	Mukhrani	56.34
	Natakhtari	56.35
	Natakhtari New	56.35
Agriculture	Saguramo	50.25
	Lami-Misaktsieli	24.79

Water priority demands were inputted to reflect the current Georgian water policies [7] (GWP, personal communication, 3 May 2017) in place and are as follows: Urban and Domestic, Hydropower, Environmental/Sanitary, the Zhinvali Reservoir, the Bodorna Reservoir, Agriculture, and other, ranging from highest priority to lowest, respectively.

2.2. Shared Vision Planning

The shared vision planning process considered three main activities: structured public participation process, the use of traditional planning techniques and the use of a computer modeling tool. For the structured public participation process, four activities were performed. First, a kickoff meeting was organized to introduce all the participants of the project and stakeholders. The authors collaborated with a local counterpart from Georgia who shared their institutional contacts, organized the events, and provided feedback during the model construction and results at every step of the project. Second, individual meetings took place with people from governmental agencies, where data and key description of the system's operation was shared. Third, a midterm project meeting was organized to provide an update on the project and receive feedback. Fourth, a final meeting was organized for sharing results, discussing the implication of the different scenarios and making sure that people in Georgia were able to use this model; a tutorial and a workshop were given to the people involved in this project. Most of the meetings used translation services that allowed for adequate communication; however, the rhythm of the meetings was slow. Individual meetings allowed for faster communications and after-work conversations, and a field trip allowed for improving communication among individuals, thrust building, and an improved understanding of the region. This research study used traditional techniques such as a simulation model that performs a water balance every time step of the period of hydrologic simulation. The use of a computer modeling tool allowed for an improved representation of the hydrology, water allocation, and use of water in the Aragvi Basin. The authors developed an interface in Excel® that allowed participants to test scenarios of their interest without learning the complexity of WEAP. This interface tool was very well received by the participants and technical staff at the governmental and non-governmental institutions.

2.3. Performance Criteria

We utilized five common performance criteria in water resources: (1) reliability in time (Rel^i_{time}) that represents the percentage of time (the probability) that a water (or electricity) demand was fully supplied, for a given user i in a given time-step t; in other words, when the deficits are equal to zero ($D^i_t = 0$) over the number of time steps (n). For instance, a 75% reliability in time means that for 75% of the period of analysis (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 (Equation (9)).

$$Rel^i_{time} = \frac{No.\,of\ times\ D^i_t = 0}{n} \tag{9}$$

(2) Reliability in volume (Rel^i_{vol}) that represents the overall amount of water that a water user received ($\sum_{t=1}^{t=n} Supplied^i_t$), compared to the water demand requested ($\sum_{t=1}^{t=n} Demand^i_t$) in the POA, in percentage (Equation (10)). 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.

$$Rel^i_{vol} = \frac{\sum_{t=1}^{t=n} Supplied^i_t}{\sum_{t=1}^{t=n} Demand^i_t} \tag{10}$$

(3) Resilience (Res^i), representing the probability of recovery (of being fully supplied) once a user's water supply has failed (in this case its full water demand was not supplied) (Equation (11)). 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.

$$Res^i = \frac{No.\,of\ times\ D^i_t = 0\ follows\ D^i_t > 0}{No.\,of\ times\ D^i_t > 0\ occurred} \tag{11}$$

(4) Vulnerability (Vul^i), representing the severity of water deficits that a determined water user can experience (Equation (12)). 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. Vulnerability becomes a similar measure to reliability and resilience (higher values are preferred) when subtracted from one.

$$Vul^i = \frac{\frac{(\sum_{t=0}^{t=n} D^i_t)}{No.\,of\ times\ D^i_t>0\ occurred}}{Water\ demand^i} \tag{12}$$

(5) Maximum deficit $(Max(D))$, representing 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.

To evaluate and compare system performance under different operation scenarios, we calculated the Water Resources Sustainability Index (SI^i) as proposed by Loucks [15] and later enhanced by Sandoval et al. [16]. Since the SI was introduced by Loucks (1997), numerous studies used the sustainability index to evaluate the performance of water resources systems. These studies include applications in groundwater sustainability studies [17], water use under climate change and irrigation management [18], water distribution systems [19], and water allocation systems that include environmental flows [20–22]. The *SI* is the geometric average of M performance criteria C^i_m for each water user i (Equation (13)) [16].

$$SI^i = \left[Rel^i_{Vol} * Rel^i_{time} * Res^i * \left(1 - Vul^i\right) * Max(D)\right]^{\frac{1}{5}} \tag{13}$$

Therefore, the *SI* summarizes commonly used performance criteria into a single index to evaluate and compare the overall performance of different strategies.

3. Results and Discussion

The Aragvi model was used to evaluate the impact of scenarios that consider different population growths (from 0% to 2.5%) for Tbilisi as well as hydropower production targets (from 0% to 200%). Although the model serves as an open-ended planning tool, preliminary results were gathered regarding the aforementioned performance criteria on the cities of Tbilisi, Zhinvali, and Dusheti and in regard to hydropower production. Utilizing the model, we quantified each of the performance criteria metric for combination of scenarios that reflect (1) a population growth rate for Tbilisi, from 0%, which represents about 1.13 million inhabitants fixed throughout the POA, to a 2.5% growth increase, which represents an increase in the initial population of 1.13 million inhabitants to 2.57 million inhabitants by 2050; and (2) 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, which is unlikely to occur) to 175% of current generation ($1.75 \times 411.3 = 719.7$ Million Kw-h per year) in 25% increments.

3.1. Tbilisi

For Tbilisi, time-based reliability will be met at all times (100% time-based reliability) when it incurs a combination of low population growth ($\leq$0.5% per year) and low hydropower generation ($\leq$75% of current hydropower generation). 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 continues decreasing. Similarly, as hydropower production increases, the times that Tbilisi can be fully supplied decreases. Under current conditions (0% 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 decreases more rapidly with an increase in hydropower production than by an increase in population. Therefore, the water supply reliability of Tbilisi is more affected by an increase in hydropower production than by an increase in population growth (Table 3).

Table 3. Time and volume-based reliability for Tbilisi.

		Reliability Time						Reliability Volume					
		Population Growth (%)						Population Growth (%)					
		0	**0.5**	**1**	**1.5**	**2**	**2.5**	**0**	**0.5**	**1**	**1.5**	**2**	**2.5**
Hydropower Production	0–75%	100	100	97	67	50	42	100	100	99.9	96	90	83
	100%	94	92	86	53	39	39	99.8	99.8	99.8	96	90	83
	125%	69	61	53	31	22	19	99	99	99	95	89	82
	150%	53	44	36	19	17	11	99	99	98	94	88	81
	200%	53	44	36	17	14	11	99	98	98	94	87	80

Volumetric-based reliability for Tbilisi 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 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 demonstrate that the volume that can be supplied to Tbilisi decreases as population and hydropower demand increase. Population increase has a proportionately higher effect on the water supplied compared to hydropower demands. This is because the City of Tbilisi has higher priority than the hydropower production.

The criterion of vulnerability (Table 4) expresses the severity of the deficit when they happen as its average percentage of deficit with respect to the water demand. 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 production increases. Again, as the population size increases, the vulnerability increases in higher proportion than with an increase in hydropower production.

Table 4. Vulnerability as the average deficit percentage with respect to water demand for Tbilisi.

		Vulnerability					
		Population Growth (%)					
		0	**0.5**	**1**	**1.5**	**2**	**2.5**
Hydropower Production	0–75%	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

For Tbilisi, the maximum deficit experienced in the POA is 42%, or in other words, at most 42% of Tbilisi's water demand will be left unmet (Table 5). 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.

Table 5. Maximum Deficit (% of water demand) and Resilience for Tbilisi.

		Maximum Deficit						Resilience					
		Population Growth (%)						Population Growth (%)					
		0	**0.5**	**1**	**1.5**	**2**	**2.5**	**0**	**0.5**	**1**	**1.5**	**2**	**2.5**
Hydropower Production	0–75%	0	0	1	16	29	40	100	100	0	0	0	0
	100%	4	0.04	4	16	29	40	100	100	40	12	5	5
	125%	4	0.04	5	19	31	42	55	57	47	20	11	7
	150%	7	0.08	8	19	31	42	35	35	26	1	7	0
	200%	13	0.14	17	22	31	42	35	35	26	7	3	0

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 $\leq$100% (Table 5). 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 (Zhinvali-Bodorna, Saguramo, Mukhrani and Natakhtari). Resilience decreases as population increases 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 increases there is a decrease in resilience, although this is not as dramatic as with the increase in population growth.

The sustainability index (SI) summarizes the previous results into one criterion (Table 6). The SI is 100% (all five performance criteria are met) for a population growth of 0, and 0.5% with hydropower production scaled down to 75%. When population increases (>0.5), the SI is zero because of its resilience; when the system fails, it never recovers. In addition, the current water demand is already at risk; there has not been a drought that has reduced the water supply for Tbilisi, but results considering similar hydrologic conditions (1987 to 2016) show that water cannot be fully supplied. An increase in hydropower production from current conditions may also compromise the water supply for Tbilisi.

Table 6. Sustainability index for Tbilisi.

		Sustainability Index					
		Population Growth (%)					
		0	**0.5**	**1**	**1.5**	**2**	**2.5**
Hydropower Production	0–75%	100	100	0	0	0	0
	100%	98	97	80	54	40	37
	125%	81	80	74	54	42	35
	150%	70	67	61	43	36	0
	200%	69	66	59	38	30	0

3.2. Hydropower

The average annual hydropower production peaks at 125% (Table 7). Hydropower production at the Zhinvali reservoir will be met at all times (100% time-based reliability) when the hydropower production target is equal to or less than 75%, regardless of population growth (Table 8). The water supply reliability of hydropower production in the Zhinvali reservoir is only affected by the hydropower production target, or, rather, it is not affected by an increase in the population growth during this period of analysis. 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 Zhinvali reservoir can be met. This percentage decreases rapidly when the hydropower production target is increased.

Table 7. Average annual hydropower production (in million kWh per year) for Zhinvali Reservoir.

		Average Annual Hydropower Production					
		Population Growth (%)					
		0	0.5	1	1.5	2	2.5
Hydropower Production	0%	0	0	0	0	0	0
	25%	113.2	113.1	113	112.9	112.8	112.8
	50%	232.2	232.2	232	231.8	231.7	231.7
	75%	335.5	335.5	335.5	335.5	335.5	335.5
	100%	404.1	404.1	404.2	404.2	404.3	404.3
	125%	409.7	409.9	410.1	410.3	410.3	410.4
	150%	407.1	407.3	407.6	407.8	407.9	408
	175%	397.6	397.9	398.3	398.5	398.6	398.8

Table 8. Time-based reliability, Volume-based reliability, Maximum Deficit, and Resilience for hydropower production of Zhinvali Reservoir.

		Reliability-Time	Reliability-Volume	Vulnerability	Maximum Deficit	Resilience
		Population Growth (%)				
		0–2.5	0–2.5	0–2.5	0–2.5	0–2.5
Hydropower Production	0%	100	100	0	0	100
	25%	100	100	0	0	100
	50%	100	100	0	0	100
	75%	100	100	0	0	100
	100%	93	96	57	92	33
	125%	71	79	61	94	21
	150%	48	54	63	100	16
	175%	35	27	67	98	12

In general, volumetric-based reliability for hydropower at the Zhinvali Reservoir decreases rapidly with higher hydropower production targets. However, hydropower generation is not sensitive to an increase in population, due to the climate seasonality. During wet months there is enough water from precipitation to produce energy, while during dry months there is simply no water to produce electricity. The amount of water that can be passed through the turbines is only affected by an increase in hydropower production.

For hydropower generation, there is an abrupt increase in vulnerability (average deficit) when the hydropower production target is above 75%. Similarly, the vulnerability of hydropower production is dependent on the hydropower production target. For hydropower production in the Zhinvali reservoir, the maximum deficit experienced in the POA 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 to the previous performance criteria, as the water production target increases the maximum deficit also increases.

In terms of the resilience of hydropower production, the water supply will recover 100% of the hydropower production if the target is equal to or less than 75% of the current hydropower diversion. Once the hydropower production target exceeds this percentage ($\leq$100%), the capacity of the system to recover from deficits drop drastically to 33% or less. Similarly to the previous performance criteria, as the water production target increases, the resilience of the system decreases (Table 8).

Table 9 shows the SI for hydropower production. When hydropower production is 75% or less of current production, the SI is 100%. Because water availability varies year to year, it is difficult to maintain a 100% under current conditions. It also looks very unlike to increase hydropower production in the future because of high interannual water variability.

Table 9. Sustainability Index for Hydropower Production.

		Sustainability Index					
		Population Growth (%)					
		0	**0.5**	**1**	**1.5**	**2**	**2.5**
Hydropower Production	0–75%	100%	100%	100%	100%	100%	100%
	100%	40%	40%	40%	40%	40%	40%
	125%	31%	31%	31%	31%	31%	31%
	150%	23%	23%	23%	23%	23%	23%
	200%	15%	15%	15%	15%	15%	15%

3.3. Agriculture

For agricultural water demands (the Saguramo, Lami-Misaktsieli, Bulachauri, Aragvispiri and Bagitchali Irrigation districts) downstream of the Zhinvali reservoir, time-based reliability depends on both hydropower production target and population growth. In general, as population increases, the water supply reliability decreases because less water is available (Table 10). In contrast, the water supply reliability is around 80% when the hydropower production target is equal to or less than 50%. This means that there is not enough water left over after hydropower generation to be taken by irrigation districts. The time-based reliability is 100% when the hydropower production is set at 75% or 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%, irrigation districts start suffering again because there is not enough water stored in the reservoir during drought periods, and water shortages resume. In terms of volumetric reliability, the overall water supply for irrigation districts is quite high, at least 98% of the total volume requested or higher.

Table 10. Time and volume-based reliability for agriculture demands.

		Reliability Time						Reliability-Volume					
		Population Growth (%)						Population Growth (%)					
		0	**0.5**	**1**	**1.5**	**2**	**2.5**	**0**	**0.5**	**1**	**1.5**	**2**	**2.5**
Hydropower Production	0%	100	100	100	91	85	82	100	100	100	99.9	99.8	99.7
	25%	100	100	100	91	85	82	100	100	100	99.9	99.8	99.7
	50%	100	100	100	91	85	82	100	100	100	99.9	99.8	99.7
	75%	100	100	100	100	100	100	100	100	100	100	100	100
	100%	100	100	100	100	100	100	100	100	100	100	100	100
	125%	100	100	97	97	97	97	100	100	100	99.8	99.7	0
	150%	97	97	91	88	85	85	1	1	100	1	0.99	0.99
	200%	91	91	85	76	73	73	100	100	100	99.2	98.7	98.4

The vulnerability for agriculture is relatively small (Table 11); it will vary from 6% to 0% for all the different scenario combinations. The worst performance for vulnerability occurs at the intersection of high population growth (>1%) and hydropower production increase (>125%). Table 12 shows the results for the maximum deficit and resilience criteria. Result for maximum deficit follow the same pattern as vulnerability; high maximum deficits are not expected unless there is a high increase in population and hydropower production. Agriculture is highly resilient across almost all scenarios. The position of agriculture downstream of a hydropower demand makes it very resilient in terms of receiving water form hydropower if it is not diverted by Tbilisi. Additionally, water demands for agriculture are small, compared to hydropower and municipal uses.

Table 11. Vulnerability as the average deficit percentage with respect to water demand for Tbilisi.

		Vulnerability (% of Demand)					
		Population Growth (%)					
		0	**0.5**	**1**	**1.5**	**2**	**2.5**
Hydropower Production	0%	0	0	0	1	1	2
	25%	0	0	0	1	1	2
	50%	0	0	0	1	1	2
	75%	0	0	0	0	0	0
	100%	0	0	0	0	0	0
	125%	0	0	2	6	6	6
	150%	2	2	2	3	4	5
	200%	2	2	3	3	5	6

Table 12. Maximum Deficit (% of water demand) and Resilience for Agriculture.

		Max. Deficit (% of Demand)						**Resilience (%)**					
		Population Growth (%)						**Population Growth (%)**					
		0	**0**	**0.5**	**1**	**1.5**	**2**	**0**	**0.5**	**1**	**1.5**	**2**	**2.5**
Hydropower Production	0%	0	0	0	2	2	3	100	100	100	100	100	100
	25%	0	0	0	2	2	3	100	100	100	100	100	100
	50%	0	0	0	2	2	3	100	100	100	100	100	100
	75%	0	0	0	0	0	0	100	100	100	100	100	100
	100%	0	0	0	0	0	0	100	100	100	100	100	100
	125%	0	0	2	6	6	6	100	100	100	100	100	100
	150%	2	2	2	6	6	10	100	100	100	100	100	100
	200%	2	4	6	9	17	21	100	100	80	75	78	78

Table 13 shows the SI for agricultural water users. Agriculture is affected Tbilisi, by population growth greater than 1% will reduce the water supply performance for agriculture. In addition, any increase in hydropower production above 100% will also affect the water supply for agriculture.

Table 13. Sustainability Index of Agriculture.

		Sustainability Index					
		Population Growth (%)					
		0	**0.5**	**1**	**1.5**	**2**	**2.5**
Hydropower Production	0–50%	100	100	100	98	96	95
	75%	100	100	100	100	100	100
	100%	100	100	100	100	100	100
	125%	100	100	99	97	97	97
	150%	99	99	97	96	95	94
	200%	97	97	91	87	85	84

4. Conclusions

This research study showed the development of a multi-objective technical assessment of water resources in the Aragvi River Basin. This analysis show that even in a rich water availability basin, such as the Aragvi Basin, future scenarios show tradeoffs among water users, for instance, if more energy is produced, then the water supply for municipal uses (e.g., Tbilisi) will be compromised. This research study is the first of its kind in Georgia, and for the city of Tbilisi, where half of the population of Georgia lives. The model also explores a series of scenarios that show the overall water supply response for different users; thus, it provides a big picture response of the system's behavior to different conditions. The Aragvi model has been used to evaluate the impact of several scenarios that consider different population growths for Tbilisi, as well as hydropower production targets. A combination of several population growth rates (from 0% to 2.5%) and hydropower production targets (from 0% to 200%) were evaluated and analyzed. The water supply for Tbilisi depends on both its own population growth rate and the hydropower production targets set in the Zhinvali 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. Additionally, as the hydropower production target increases, the water supply for Tbilisi becomes less reliable since less water is left stored in the Zhinvali reservoir. The water supply for Tbilisi is more vulnerable to increases in hydropower production than increases in population. Currently, Tbilisi has a water supply reliability of 97%, which means that a water deficit can occur in one out of 35 years. Population increase and climate change can play a significant role in the reduction of the water supply reliability for Tbilisi.

Hydropower production in the Zhinvali 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 reduced as the hydropower production target increases.

Agriculture demands depend on both population growth rate and hydropower production targets. At low hydropower production, the irrigation districts experience water supply deficits because there is not enough water passed through the turbines or left in the Aragvi River. When the hydropower production target is set at 75% or 100%, the water supply reliability for irrigation districts is optimal, and they receive their full water demand at all times regardless of 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 due to 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.

Stakeholders welcomed the development of the Aragvi Model and realized how fragile the system is. Before this study, the common understanding was that there was enough water in the Aragvi basin to supply water for Tbilisi and produce electricity without any compromise on both objectives. After seeing our results and discussing the tradeoffs, it was clear that the system is on the verge of being stressed and that actions could be taken, such as reducing the conveyance losses that account for a significant amount of water. Stakeholders also welcomed the development of tutorial materials for the use of the model and the interface, so they feel that they could explore their own ideas; in fact, the interface always compares two scenarios: the Baseline scenario and a user defined scenario called My Scenario. Stakeholders appreciated the authors' effort in putting all these materials and tools together for their benefit.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, investigation, formal analysis, resources, supervision, project administration, S.S.-S. and J.P.O.-P.; investigation, data curation, writing—original draft preparation, writing—review and editing, visualization, S.S.-S., J.P.O.-P., and L.F.; funding acquisition, S.S.-S. All authors have read and agreed to the published version of the manuscript.

Funding: Part of this work was prepared under the United States Agency for International Development (USAID) Governing for Growth (G4G) in Georgia Project "Piloting Water Allocation Modeling Using WEAP in the Aragvi River Basin"; contract number RFA#2017-003. The author's views expressed in this publication do not necessarily reflect the views of either of the organizations.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The following link is a repository of the model, model documentation, input data and the interface: https://doi.org/10.4211/hs.6f1043f3468c44f3b21d2261c37c5c3f.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Langsdale, S.; Beall, A.; Bourget, E.; Hagen, E.; Kudlas, S.; Palmer, R.; Tate, D.; Werick, W. Collaborative Modeling for Decision Support in Water Resources: Principles and Best Practices. *J. Am. Water Resour. Assoc.* **2013**, *49*, 629–638. [CrossRef]
2. Linnenluecke, M.K.; Verreynne, M.-L.; de Villiers Scheepers, M.J.; Venter, C. A Review of Collaborative Planning Approaches for Transformative Change towards a Sustainable Future. *J. Clean. Prod.* **2017**, *142*, 3212–3224. [CrossRef]
3. Megdal, S.; Eden, S.; Shamir, E. Water Governance, Stakeholder Engagement, and Sustainable Water Resources Management. *Water* **2017**, *9*, 190. [CrossRef]
4. Palmer, R.N.; Werick, W.J.; MacEwan, A.; Woods, A.W. Modeling Water Resources Opportunities, Challenges and Trade-Offs: The Use of Shared Vision Modeling for Negotiation and Conflict Resolution. In *WRPMD'99: Preparing for the 21st Century*; American Society of Civil Engineers: Reston, VA, USA, 1999; pp. 1–13.
5. Jacobs, K.; Lebel, L.; Buizer, J.; Addams, L.; Matson, P.; McCullough, E.; Garden, P.; Saliba, G.; Finan, T. Linking Knowledge with Action in the Pursuit of Sustainable Water-Resources Management. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 4591–4596. [CrossRef] [PubMed]
6. Voinov, A.; Gaddis, E.J.B. Lessons for Successful Participatory Watershed Modeling: A Perspective from Modeling Practitioners. *Ecol. Model.* **2008**, *216*, 197–207. [CrossRef]
7. ED; USAID. *Report on Existing Patterns of Water Use in the Aragvi River Basin*; Piloting water allocation modeling using WEAP in the Aragvi River Basin; Environment and Development, United States Agency for International Development: Washington, DC, USA, 2017; p. 34.
8. GWP. Water Supply Sources and Rivers. Available online: https://www.gwp.ge/en/watersources (accessed on 26 December 2021).
9. Petersen, G.; Bakhtadze, M. *White Paper on Water Allocation Planning Framework*; USAID Governing for Growth in Georgia: Tbilisi, Georgia, 2017.
10. Ministry of Energy of Georgia Elektrosadgurebis Nuskha 1105 Geo. Available online: http://www.energy.gov.ge/projects/pdf/news/Elektrosadgurebis%20Nuskha%201105%20geo.pdf (accessed on 20 February 2018).
11. ESCO. *Electricity Balance of Georgia*; Electricity System Comercial Operator: Tbilisi, Georgia, 2015.
12. Yates, D.; Sieber, J.; Purkey, D.; Huber-Lee, A. WEAP21—A Demand-, Priority-, and Preference-Driven Water Planning Model: Part 1: Model Characteristics. *Water Int.* **2005**, *30*, 487–500. [CrossRef]
13. Sandoval-Solis, S.; Ortiz-Partida, J.P.; Hartsough, P.; Floyd, L.; Bakhtadze, K.; Kheladze, N.; Sukhishvili, L.; Barnovi, E.; Kobulia, I. *Documentation and Testing of the Aragvi River Basin Planning Model and Evaluation of Water Management Strategies*; Water Management Lab, University of California, Davis: Davis, CA, USA, 2017; p. 63.
14. Sandoval-Solis, S.; Ortiz-Partida, J.P.; Floyd, L. Aragvi River Basin Model. *Hydroshare Online Data Repos.* **2022**. [CrossRef]
15. Loucks, D.P. Quantifying Trends in System Sustainability. *Hydrol. Sci. J.* **1997**, *42*, 513–530. [CrossRef]
16. Sandoval-Solis, S.; McKinney, D.C.; Loucks, D.P. Sustainability Index for Water Resources Planning and Management. *J. Water Resour. Plan. Manag.* **2011**, *137*, 381–390. [CrossRef]
17. Mays, L.W. Groundwater Resources Sustainability: Past, Present, and Future. *Water Resour. Manag.* **2013**, *27*, 4409–4424. [CrossRef]
18. Santikayasa, I.P.; Babel, M.S.; Shrestha, S.; Jourdain, D.; Clemente, R.S. Evaluation of Water Use Sustainability under Future Climate and Irrigation Management Scenarios in Citarum River Basin, Indonesia. *Int. J. Sustain. Dev. World Ecol.* **2014**, *21*, 181–194. [CrossRef]
19. Dziedzic, R.M.; Karney, B.W. Water Distribution System Performance Metrics. *Procedia Eng.* **2014**, *89*, 363–369. [CrossRef]
20. Lane, B.A.; Sandoval-Solis, S.; Porse, E.C. Environmental Flows in a Human-Dominated System: Integrated Water Management Strategies for the Rio Grande/Bravo Basin. *River Res. Appl.* **2015**, *31*, 1053–1065. [CrossRef]
21. Safavi, H.R.; Golmohammadi, M.H.; Sandoval-Solis, S. Expert Knowledge Based Modeling for Integrated Water Resources Planning and Management in the Zayandehrud River Basin. *J. Hydrol.* **2015**, *528*, 773–789. [CrossRef]
22. Sandoval-Solis, S.; McKinney, D.C. Integrated Water Management for Environmental Flows in the Rio Grande. *J. Water Resour. Plan. Manag.* **2014**, *140*, 355–364. [CrossRef]