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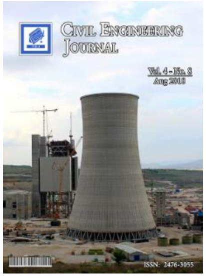

Drought Scenario Analysis Using RiverWare: A Case Study in Urumqi River Basin, China

Shalamu Abudu [a*], Zhuping Sheng [a], Hamed Zamani Sabzi [b], James Phillip King [c]

[a] *Texas A&M AgriLife Research and Extension Center at El Paso, 1380 A&M Circle, El Paso, TX, USA 79927-5020.*

[b] *Dept. of Geography and Environmental Sustainability, University of Oklahoma, 100 East Boyd St, SEC Suite 662, Norman, OK 73019.*

[c] *Dept. of Civil Engineering, New Mexico State University, MSC 3CE, PO Box 30001, Las Cruces, NM, USA 88003.*

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Abstract

In this study, we applied RiverWare modeling approach to evaluate the management decisions on surface water and groundwater diversions in the agricultural watershed of the Urumqi River Basin of Xinjiang in Northwestern China. A rule-based daily time step RiverWare model was developed to simulate the hydrologic effects of different water management alternatives considering irrigation and drainage systems, crop water use, and diversion rules at the diversion dams within the basin. Daily data period from 2005 to 2009 was used to calibrate the model and 2010-2012 was used to validate the model. A calibrated daily RiverWare model was then used to evaluate the management decisions under different drought scenarios that generated by using the snowmelt runoff model (SRM) that developed to simulate inflow from upstream of Yingxiongqiao gaging station. Two drought scenarios (reduced precipitation and increased temperature) analysis were performed, and the corresponding hydrological variables were compared to the baseline scenario. The results indicated that the model adequately reproduced the historical inflows for the Wulabo Reservoir. The scenario analysis results suggest that the reduced precipitation led to increased groundwater pumping for irrigation both in the spring and summer. The increased temperature induces a significant increase in surface runoff in the basin and leads to increased crop water demand within the irrigation district, and however does not necessarily reduce the groundwater pumpage. Water operation policies from RiverWare provide guidelines for conjunctive use of groundwater and surface water resources within the basin under different water supply scenarios in the future.

Keywords: RiverWare Model; Drought Scenario Analysis; Surface Water; Groundwater; Snowmelt Runoff Model (SRM); Scenarios.

1. Introduction

Mountain snowmelt-fed rivers in northwestern China are the primary water resource supply for public use, agriculture irrigation, environmental use, hydropower and other purposes. In recent years, global climate change has already affected the local hydrology and water cycle in these areas [1]. Notably, the glacier and snow-covered areas were influenced as they are susceptible to temperature factor, and can affect the timing and magnitude of the streamflow in this region significantly [2, 3]. Due to increasingly frequent and severe periods of drought and growing demand, the river alone no longer meets the regional water needs, leading to increased groundwater extraction and dropping water tables [4]. This is especially true in the Upper Urumqi River Basin, which supports the primary vegetable supplier to the populous Urumqi, the capital city of the Xinjiang Uyghur Autonomous Region, China. The Upper Urumqi River Basin is in the middle portion of the northern flank of the Tianshan Mountains, about 175 km from Urumqi. Persistent drought, climate change and population growth in the region pose significant challenges in the management of limited water

* Corresponding author: shalamu3@gmail.com

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resources, particularly in the lower Urumqi river basin. As stream water is a critical water supply for Urumqi city, the streamflow characteristics and changes have drawn considerable attention with the rapid population growth and water shortage under climate change. Many studies have been conducted in the basin over last decades, including groundwater and surface water supply variations in the agricultural basin upstream from Wulabo reservoir, how its reaction to the changing environment including frequent drought, population growth and sharply increased water demand in the area.

One of the approaches in the arid region to meet demands during the drought is the conjunctive use of surface water and groundwater. This technique might be especially important as a buffer function for mitigating impacts of drought, such as increased heat and reduced precipitation [5]. In general, two-way exchange between surface water and groundwater directly affects the quality and quantity of surface water and groundwater bodies, which not only impact on the water chemical composition and evolution but also alter groundwater and ecological balance. The interaction is often complicated by human activities and climate change including surface water diversion, groundwater pumping, and irrigation, as they could significantly alter the flow regimes of both surface water and groundwater [6, 7]. Hence, understanding the complex behavior of the integrated surface water and groundwater system is very important to the regional water resources management [8]. There are many research results reported in the literature for coupling surface and subsurface flow across a range of scales into proper deliberation of regional water management policies in the last decades [8-12]. Many models were developed and applied in modeling of the interaction of groundwater and surface water for over forty years. To name a few, Sokrut (2001) developed the integrated model, here called ECOFLOW, based on the source codes of groundwater flow model (MODFLOW-88) and physically distributed watershed model (ECOMAG) [13]. Markstrom et al. (2008) developed an integrated hydrologic model called GSFLOW (Ground-water and Surface-water FLOW) based on the integration of the U.S. Geological Survey Precipitation-Runoff Modeling System (PRMS) and the U.S. Geological Survey Modular Ground-Water Flow Model (MODFLOW) [14]. Kim et al. (2008) proposed a new approach whereby the characteristics of the hydrologic response units (HRUs) in the SWAT model are exchanged with cells in the MODFLOW model [15]. Tian et al. (2015) developed a new model coupled with the Storm Water Management Model (SWMM), and Ground-Water and Surface-Water Flow Model (GSFLOW). The new (GSFLOW) model was applied to study the hydrologic cycle of the Zhangye basin, northwest China, a typical arid to the semi-arid area with significant irrigation [16].

In this study, we have utilized RiverWare model in addressing the management decisions on surface water diversions and groundwater withdrawal under several drought scenarios in Urumqi River Basin. RiverWare™ is a general-purpose river and reservoir modeling application developed by the Center for Advanced Decision Support for Water and Environmental Systems of the University of Colorado in collaboration with the Tennessee Valley Authority, the U.S. Bureau of Reclamation and the U.S. Army Corp of Engineers. RiverWare can be run either as a stand-alone application or in concert with other models and databases. It can be used to simulate hydrologic responses of river systems, given regulated inflows and management decisions such as reservoir releases, diversions and return flows. Models are built using a palette of objects that represent features in the basin and user selectable methods that characterize physical processes. The model can be used to simulate river flow and water operations decisions as well as conjunctive management scenarios in a river basin by incorporating physical layout of diversions, reaches, crop and riparian water depletion, groundwater sub-basins, drains, canals, etc. RiverWare is currently used for planning and scheduling operations in several river basins in the United States such as the Middle Rio Grande, Truckee-Carson, Colorado River, and Tennessee Valley [17]. RiverWare model had been developed for Middle Rio Grande for flood control planning and water operations. Since 2010, research efforts have been dedicated to establishing this RiverWare model to simulate water operations in the Rio Grande reach starts from Elephant Butte Reservoir to the Rio Grande at El Paso gaging station [18-19].

It is the viability of RiverWare in river and reservoir system modeling which drives us to use the model in addressing the issues in highly-managed Urumqi River Basin, particularly under drought scenarios. We tried to answer what-if questions in the changing environment in the basin using drought scenario analysis by linking the results of previously developed snowmelt runoff model (SRM) in the mountainous upper Urumqi River Basin [20-22] and calibrated RiverWare model that developed in the lower agricultural basin upstream from Wulabo Reservoir. For that purpose, this study is considering the management decisions on surface water and groundwater diversions in the agricultural basin in the vicinity of the river corridor and the irrigated agricultural area within the river basin. A rule-based daily time step RiverWare models were developed to simulate the hydrologic effects of different water management alternatives by considering irrigation and drainage systems, crop water use, and diversion rules at the diversion dams within the basin. RiverWare groundwater objects were added to simulate the alluvial aquifer and pumping in the irrigation district, and to quantify surface water and groundwater diversions and to evaluate the hydrologic effects of different water management alternatives. A calibrated daily RiverWare model was then used to assess the management decisions under different drought scenarios that generated by using the snowmelt runoff model (SRM) that developed to upstream at the outlet of the mountain (Yingxiongqiao gaging station).

2. Study Area and Data

Urumqi River basin is located at the longitude of 86° 45′ E and 87° 56′ E，latitude of 43° 00′ N and 44° 07′ N, and has an area of 4,684 km^2, the total length of 214 km, and 62.6 km up to the river outlet from Tianshan Mountain (As shown in Figure 1). According to the statistics from Yingxiongqiao hydrological station, between the years of 1958 to 2009, the average annual runoff is $2.42 \times 10^8 m^3$, the average temperature is 1.6℃, and average precipitation is 456.9 mm. The glacier and snow stored on the northern slopes of Tianshan in Xinjiang melt to feed a number of streams during the spring and summer seasons. The typical arid and semi-arid climate dominates the agricultural area where the irrigation is dependent upon the snowmelt runoff, particularly in the summer. Among them, the discharge of the Urumqi River is mainly fed by snowmelt and precipitation with proportions of 37% and 36% respectively [23].

The direction of groundwater flow in the basin is northeast, from the mountains into the valley and then north and east down to the river. Recharge to the basin is via seepage from the river and irrigation canals. Some recharge also occurs from subsurface flow through the coarse sediments in mountain front tributaries and arroyos. A single layer of coarse sand and gravel form a permeable formation of several hundred meters thick. Towards lower valley, the thickness is changing, and due to complicated river bed geology, groundwater storage is limited. In the past, the groundwater was recharged by the rivers flowing from the Tianshan Mountain into the basin, and springs discharge water from the aquifer toward the lower end of study area near Wulabo Reservoir. Recently the river water is diverted through canals and stored in reservoirs, the leakage through the river bed is not predominant, but instead, water infiltrates from delivery and field channels and irrigation losses. At the same time, groundwater is also extracted heavily by well pumping for irrigation in the agricultural area of the basin [24].

In this study, the river basin upstream from Wulabo Reservoir (located at the northeast end of the study area) is selected as the study area. The lower end of the study area is chosen as the inflow into Wulabo reservoir since no river channels exist in the lower part of Wulabo reservoir, where outflow from the reservoir is delivered to downstream via constructed canals. The study watershed is divided into two parts: (a) the upper mountainous watershed where no agricultural activities exist upstream from Yingxiongqiao gaging station. An SRM model was developed to the part of the basin for simulating snowmelt runoff at Yingxiongqiao gaging station [20]. We design drought scenarios using SRM model in this section of the river basin. (b) Lower valley where primary agricultural production occurs, downstream of Yingxiongqiao gaging station and upstream of Wulabo Reservoir, this is the main study area in this study.

There are two gage stations along the river and one meteorological station in the basin. The Yingxiongqiao gaging station is located at the mountain outlet at an altitude of 1920 m. Wulabo reservoir inflow is measures at the east edge of Urumqi city and the end of Qingnian irrigation district (lower west side agricultural area of the study area). The Daxigou meteorological station is located at the high-altitude mountain area at 3,539 m (Figure 1). Daily stream flow and weather data are available at all stations from January 1, 2005, to December 31, 2012. The period of 2005-2008 was used as a calibration period and from 2009-2012 was used for RiverWare model validation period.

The main crops in the study area include winter wheat, cotton, and vegetables. Typical irrigation techniques used in the area are flood irrigation for winter wheat, and furrow irrigation for all other row crops including cotton and most vegetables. Data utilized in the model include historical flow data at gaging stations, canal diversions, estimated water demands based on historic data, estimated seepage losses along the canals and river reach, and time lag estimated from the water operations procedure of the irrigation districts.

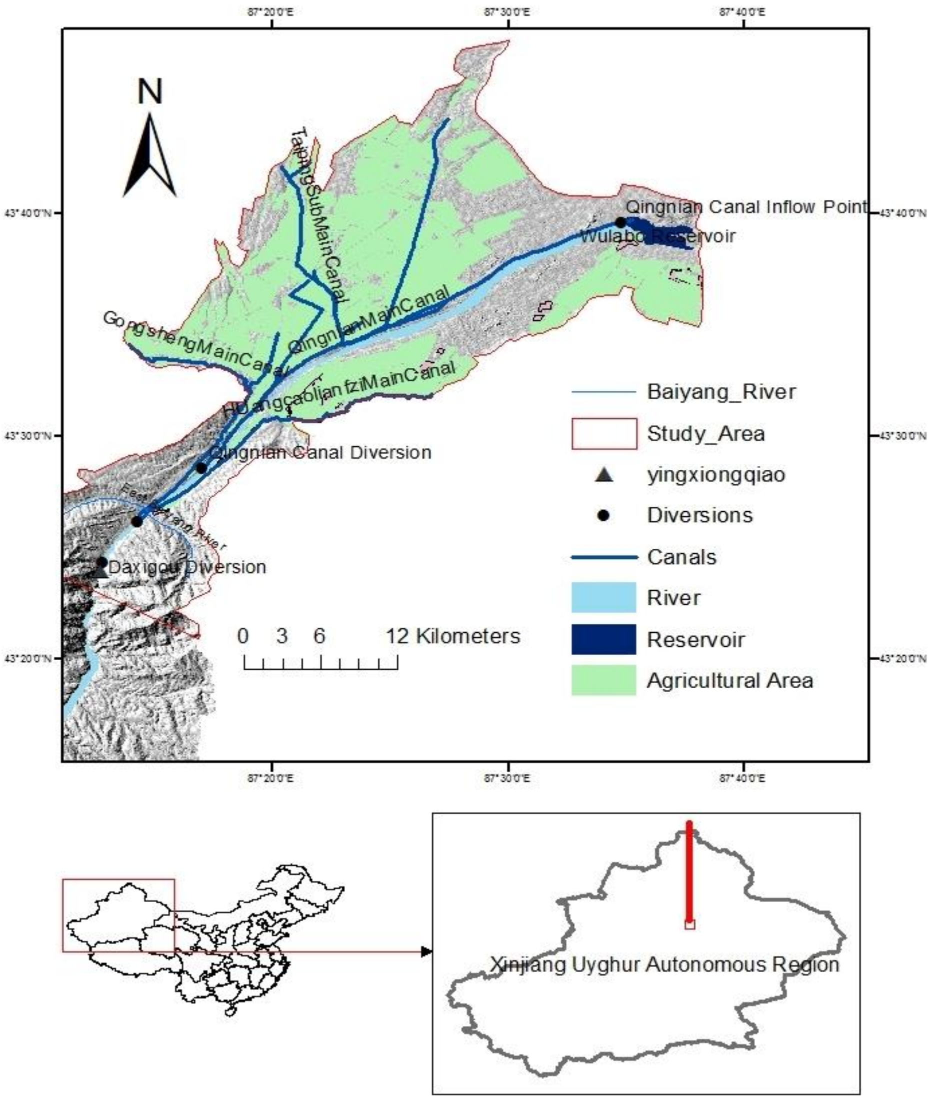

Figure 1. Location of Urumqi River Basin and Study Area

3. Methodology

The irrigation and drainage network in the study area is very complex. First, a conceptual node-link model was developed to characterize the relationships between the river, canals, laterals, and drains as well as diversion points. Then, a RiverWare model was developed to simulate water flows within the study area based on the conceptual model. RiverWare reach objects are linked directly to the groundwater objects to accomplish physical simulation of the surface-water/groundwater interaction through head-dependent flux calculations. Existing groundwater characteristics and the data necessary for simulating groundwater responses were obtained from the previous work [23, 24]. Other parameters, such as the stage-discharge rating curve, the conductance of the riverbed, and the geometry of the river bed, are determined using GIS and on-site measurements.

3.1. Conceptual Model Layout

The overall layout of the conceptual model of irrigation network within the irrigation district is shown in Figure 2. Daxigou diversion dam is located approximately 5 km downstream of Yingxiongqiao gaging station and is the initial diversion point from the river channel. At this location, water is diverted to the west side agricultural area through the Gongsheng main canal and to the east side agricultural area through the Huangcaoliangzi canal. The Gongsheng main canal diverts water to irrigate farms in the vicinity of Gongsheng village (Zhaojiahuangzi and Yongfengxiang) agricultural area. The Huangcaoliangzi canal diverts water from the mainstream to the Hangcaoliangzi water users including several agricultural village units on the east side of the river. At the downstream of Daxigou diversion, there is Qingnian canal diversion, which diverts water to the Qingnian main canal and delivers to the whole Qingnian Irrigation District on the west side of the river channel. The water from the main canals is then diverted through laterals and irrigation ditches to farm fields for irrigation or diverted for urban water users. The drainage system collects the return flow from the farm fields, discharges it downstream and returns it to the river or some sections of main channels and finally to Wulabo Reservoir. The agricultural water users were divided based on the administrative boundaries at the village level, and historical crop acreage for each water user was collected and used to estimate crop water requirement.

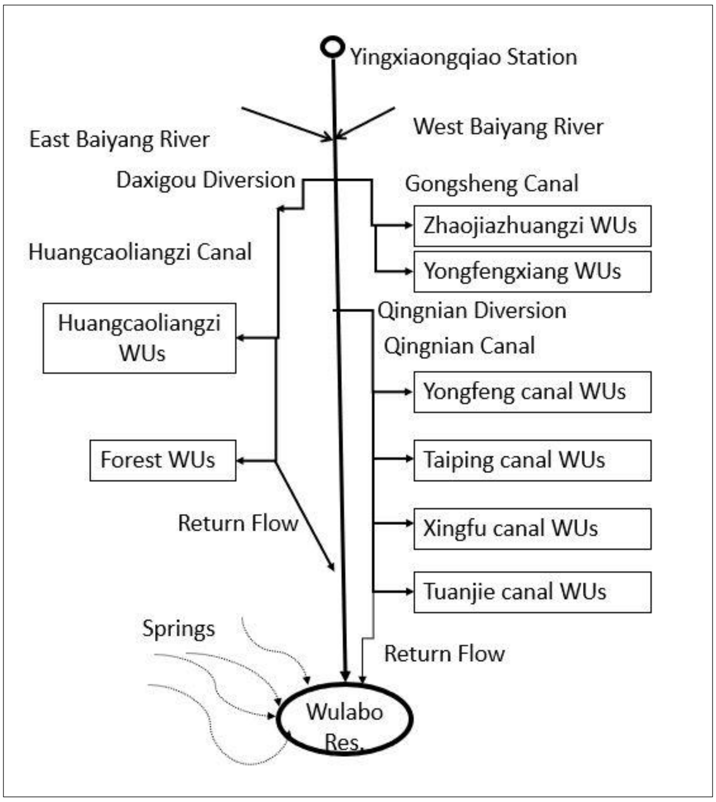

Figure 2. The conceptual model layout of the river, diversions, canals and water users (WUs) in the study area

3.2. River Ware Model Design

3.2.1. Division of Reaches and Groundwater Objects

The selected river channel is simulated by dividing into three reaches. With the addition of groundwater objects to simulate the interaction of surface-water and groundwater, the reach length was determined by the length in the downstream direction of the groundwater objects. Analysis of the slope of the river segment indicated that a reach length of 10 to 20 kilometers would be sufficient to adequately simulate the groundwater objects that are connected to river stream. Table 1 describes the division of the river reaches in the basin, from Yingxiongqiao gaging station through Wulabo Reservoir near Urumqi City. The boundaries of some of the reaches were adjusted to the location of gages or other physical structures in the river. The irrigated corridor along the lower river segments consists of two linear river segments that approximately follow the curvature of the river. Some cross-sections were surveyed in the field, and average properties for each reach were derived using GIS (As shown in Table 1).

Table 1. Properties of reaches in the study basin

Reach	Reach Name	Length (km)	Slope	Width (m)	Elevation (m)
Reach 1	Yingxiongqiao- GongshengMainCanal	16.8	0.0152	167	1641
Reach 2	GongshengMainCanal- TaipingMainCanal	9.9	0.0156	294	1427
Reach 3	TaipingMainCanal Wulabo Reservoir	16.2	0.0167	633	1236

The groundwater objects (GWOs) in RiverWare simulate the losses to and gains from the river. The shallow groundwater system is simulated by River Ware groundwater objects in the model with head-dependent flux between groundwater objects and the river, drains, other groundwater objects, and the deep aquifer. The simulation of the shallow groundwater system was completed using a horizontal course discretization. In each reach, a set of three groundwater objects were used to simulate the river and the surrounding irrigated areas. For the groundwater objects that are located to the east and west of the river, one boundary was the boundary of the river groundwater object, and the other boundary was either the extent of the irrigated area or the canal furthest from the river.

A shown in Figure 3, a total of six Groundwater Objects (GWOs) has been delineated in the lower valley corresponding to River Reaches 2 and 3. Groundwater objects were assigned to the Reaches 2 and 3 based on the assumption that there is one groundwater object associated with the river reaches, and one groundwater object on each side of each River Reach object, for a maximum of three groundwater objects that may be associated with each Reach Object. No GMOs were designed in the area related to Reach 1, since there is no irrigated area exists in this section of the river. The groundwater objects also interact with deeper groundwater layers by use of the deep percolation option of the groundwater object. The locations of the areas represented by groundwater objects are shown in Figure 3.

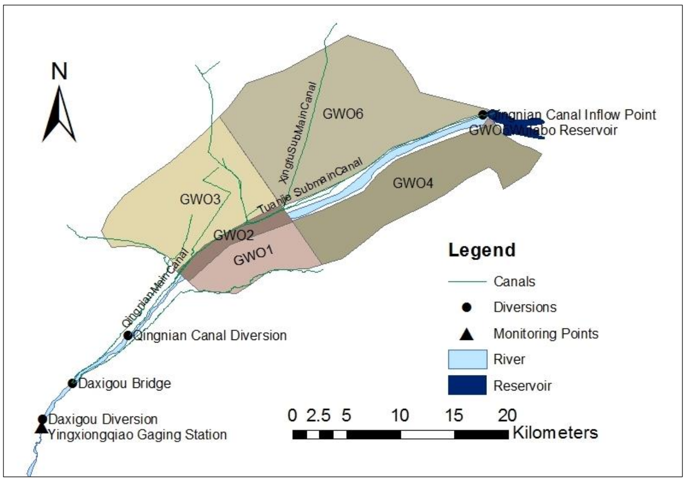

Figure 3. Delineation of Groundwater Objects (GWOs) in the study basin

3.2.2. River Ware Model Configuration

Based on the conceptual layout of the hydrologic system of the study area, a rule-based River Ware model at daily time steps was constructed to simulate flows in the river and irrigation network within the study area (as shown in Figure 4). A daily rule-based simulation model was developed by calibrating and validating the model for the periods of 2005-2008 and 2009-2012, respectively. The model includes the river reach from the Yingxiongqiao to Wulabo Reservoir and its associated diversion points and gaging stations, main canals and diversions into laterals, and return flows. The model also incorporates agricultural water users and groundwater pumping during the crop growing season. The rules are written to reflect the diversion operations at Daxigo diversion for Gongsheng canal and Hungcaoliangzi canal, and Qingnian diversion for Qingnian Main canal. The diversion practices are a conditional diversion at each diversion location based on the flow magnitude in the Urumqi River mainstream.

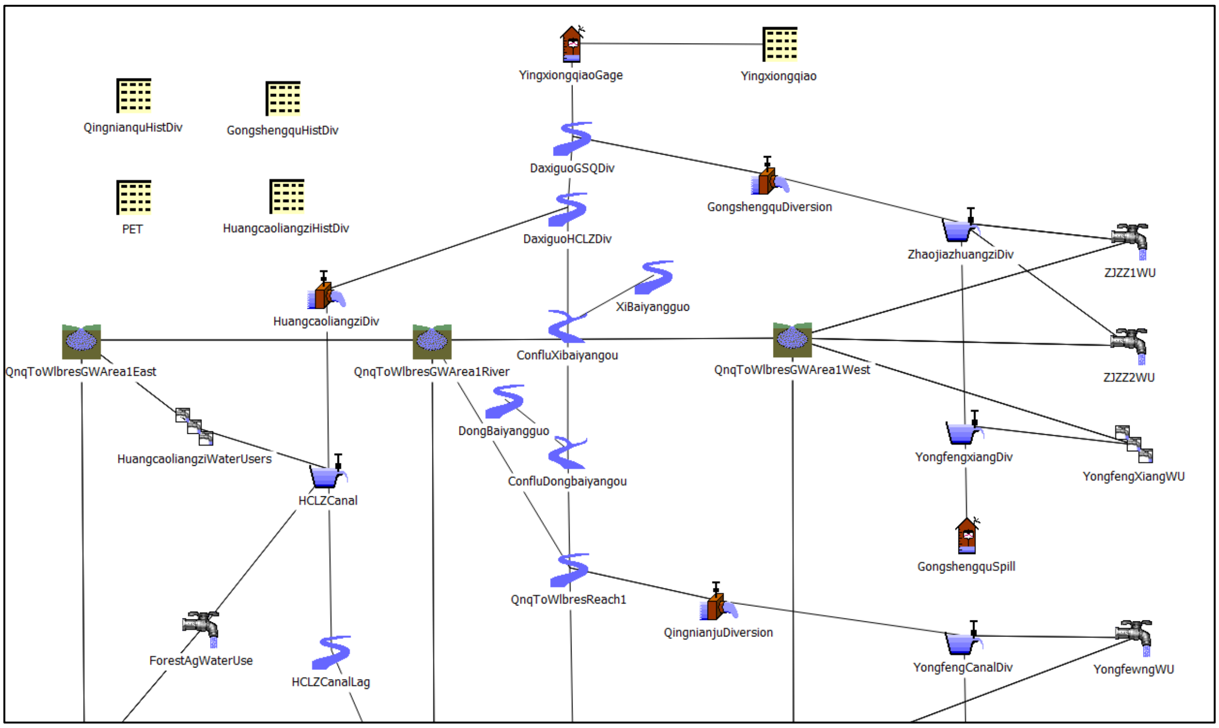

Figure 4. Part of RiverWare model layout for an agricultural area in the lower valley

Numerous RiverWare objects were used to simulate the hydrological system of the study basin; including reach, diversion, water user, and gaging stations. The Reach objects simulate river channel, canals, laterals, and drains. Seepage losses from the canal system are considered as 10% of the total flow based on the seepage losses study and historical records of the irrigation district. Diversion objects were used to account for the diversions from the river to canals and the canals to the laterals. Rules are written to reflect conditional diversions at different canal heads based on upstream flow conditions and demand from the agricultural area. The Diversion objects make a summation of inflows and outflows at each time step to determine the needed diversion from upstream. This flow rate then compounds as it migrates from the bottom of the model to the top, eventually resulting in the total required inflow for each time step.

The Water User objects are used to define the crop water consumptive use in each water user. A major component of water use in the basin is the crop consumptive use. The model simulates the crops consumptive use by using a water user object for each of the areas that are simulated by one of the east and west groundwater objects. The reference evapotranspiration is estimated using the Hargreaves and Samani equation [25] due to lack of measured data availability. Each water user object uses data for crop ET rate, crop area and farm efficiency to determine the volume of crop ET, and total return flow from surface water and groundwater. The total aggregated daily ET values and total cropland for the water user object were utilized to calculate daily total crop water use. Based on the agricultural growth data in the Qingnian irrigation district, the following average crop acreage was used to calculate crop irrigation requirements for each water users. For all of these categories, the crop coefficients and lengths of crop development stages listed in FAO Irrigation and Drainage Paper No. 56 [26] were used (As shown in Table 2.)

Table 2. Crop Coefficients and Lengths of Crop Development Stages [26]

CROP TYPE	Average Acreage (%)	Crop Coefficients (Kc)			Lengths of Crop Development Stages (days)				
		Initial	Mid	End	Initial	Developing	Mid-season	Late-season	Total
WINTER WHEAT	20	0.7	1.15	0.32	20	25	60	30	135
BARLEY	20	0.3	1.15	0.25	20	25	60	30	135
POTATO	12	0.5	1.15	0.75	25	30	45	30	130
VEGETABLES	23	0.7	1.05	0.95	30	40	40	20	130
NURSERY AND OTHERS	25	0.5	1.1	0.65	30	30	100	30	190

By combining the crop coefficients, lengths of growing periods, beginning and ending dates for growing seasons, and reference ET time series, ET time series for each of the crop categories were determined at the Qingnian irrigation district. The ET time series obtained in this manner was reduced by 10% to better estimate the water demand in calibrating the RiverWare model to the Qingnian irrigation district.

3.3. Drought Scenarios Configuration

The River Ware model has the advantages of simulating river and reservoir operations, groundwater and surface water interaction in the irrigation area and is more suitable to the complicated agricultural land located in the lower basin of the Urumqi River. Once the rule-based River Ware model calibrated and validated using historical observations, it can be used to perform drought scenario analysis using runoff variations at Yingxiongqiao gaging station and likely increased crop water use demand in the irrigation district due to a higher temperature during the drought. To design drought scenarios, we have utilized previous a Snowmelt Runoff Model (SRM) [20] that developed to the upper mountainous watershed upstream of Yingxiongqiao gaging station. The SRM model predictions at Yingxiongqiao gaging station under designed drought scenarios will be used as an input for River Ware model that was developed for the agricultural watershed from Yingxiongqiao gaging station to Wulabo Reservoir for evaluation of water supply management decisions under f drought scenarios in the Basin.

To address this, three different drought scenarios were designed based on the temperature and precipitation changes (as shown in Table 3); they are: Baseline condition - Average of daily modeled flow at Yingxiongqiao station for the years of 2005, 2006, 2007; Reduced precipitation - upper basin average precipitation reduced by 30% compared to the precipitation in the baseline condition; Increased temperature - upper basin average temperature increased by 2.5℃ compared to the temperature in the baseline condition. Based on the different scenarios, the calibrated SRM model for the watershed upstream of Yingxiongqiao station was used to generate daily runoff during snowmelt season (March through October) at Yingxiongqiao gaging station. At the same time, we assume that the precipitation change does not affect crop evapotranspiration in the irrigation district. It should be noted that, as the temperature rises, the evapotranspiration from the agricultural crop and other vegetation increases. In this study, the evapotranspiration increase under increased temperature (when temperature increases by 2.5℃) considered as 8% based on the reference evapotranspiration calculation using Hargreaves and Samani equation [25].

The generated daily runoff at Yingxiongqiao gaging station using SRM under different scenarios is then fed into River Ware model as inputs, and the increased crop water use under increased temperature scenario will be increased for each water user in the irrigation district. Then, the River Ware models rerun for different runoff and crop water use conditions under different scenarios to generate the surface water and groundwater conjunctive use water operation strategies for agricultural production in the Qingnian irrigation district within the study area.

Table 3. Scenario configuration and daily spring-summer (March-August) runoff variation at Yingxiongqiao Gaging Station

Scenario Name	Baseline	Reduced precipitation	Increased temperature
Scenario Condition	Average of 2005-2007's Simulated flow	Precipitation Reduced by 30%	Temperature Increased by 2.5℃
Spring-Summer runoff ($10^6 m^3$)	192	137	216
Runoff Volume Changes at Yingxiongqiao Station (%)	0%	-28.6%	+12.5%
Crop Evapotranspiration Changes	0%	0%	+8%

4. Results and Discussion

4.1. Model Calibration and Validation

During the calibration period (from January 1, 2005 to December 31, 2009), the selected model parameters were adjusted to minimize the difference between daily observed and reservoir inflow at Wulabo Reservoir through adjusting the initial groundwater object elevations such that the groundwater objects elevations were realistic representations of the alluvial aquifer heads, aquifer's horizontal hydraulic conductivity, and canal seepage percentage to simulate the river and drain flows. We also tried different reduced rate of ET estimates and irrigation efficiencies to match the inflow at Wulabo reservoir better. Once calibrated, the calibrated model was run for the validation period (from January 1, 2009, to December 31, 2012) using the parameters from the end of the calibration run as the initial values for the validation run. The daily inflow to the reservoir from the RiverWare simulation was compared to historically observed flows to verify that the overall flows in the model are correct.

As shown in Figure 5 and 6, the inflow values at the Wulabo Reservoir from the RiverWare simulation were compared to historic inflows to verify that the simulated flows match well with observed historic value. For inflow calibration at the Wulabo Reservoir, both time series and scatter plots between the modeled inflow and recorded inflow indicated the acceptable performance with a coefficient of determinations of 0.66 and 0.49 for calibration and validation periods, respectively. The model calibration and validation show that the developed RiverWare model captures the timing and magnitude of the inflow relatively well for the study area. It is also observed that there are some errors when simulating reservoir inflow in the summer both in calibration and validation period. This may be due to the complexity of the system at this river sections that are affected by substantial human intervention, particularly during the summer irrigation season when water demand is high.

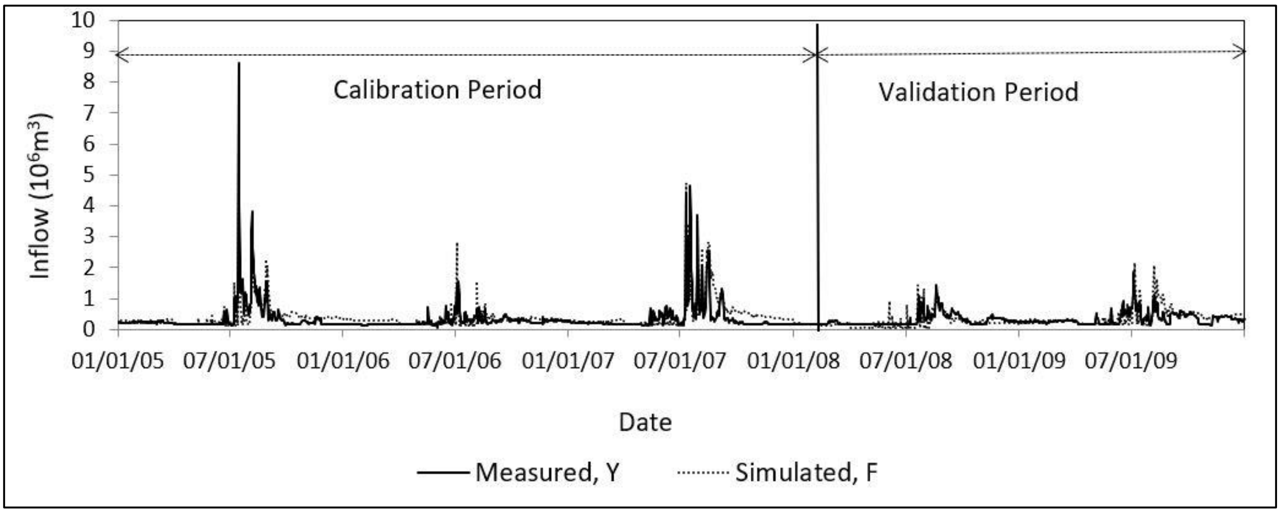

Figure 5. Daily time series plot of measured and simulated Wulabo Reservoir inflow

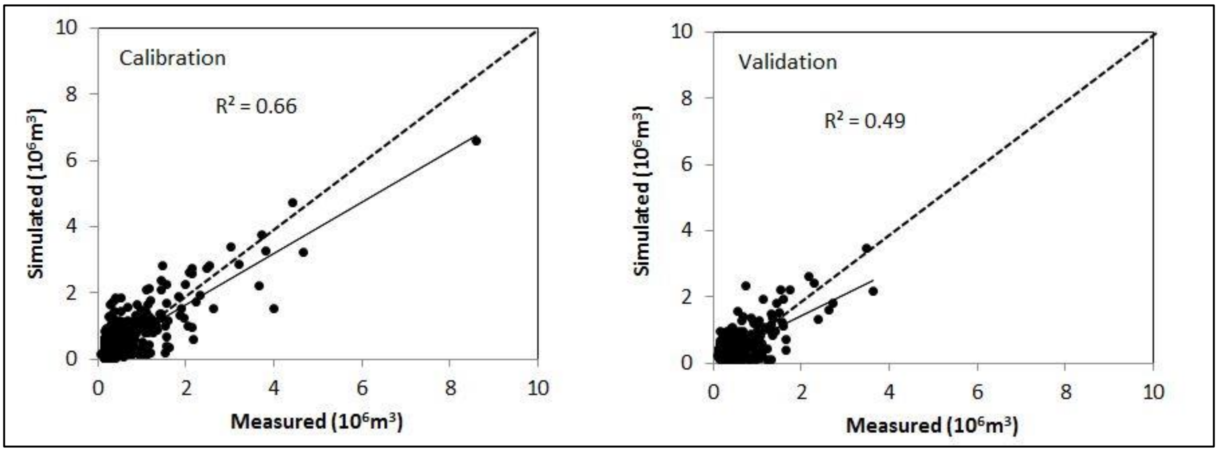

Figure 6. Scatter plot of measured and simulated daily Wulabo inflow for calibration and validation period

We also calculated the following statistical measures for calibration and validation period to evaluate the performance of the model. They are the coefficient of determination (R^2), the Mean Absolute Error (MAE), the Root–Mean-Squared Error (RMSE), Relative Root Mean Squared Error (RRE) and Nash–Sutcliffe model efficiency coefficient (NSE). The coefficient of determination is an indication of the percent of the variation of the observed salinities being explained by simulated salinity. The RMSE is a measure of the deviation of the simulated salinities from the measured salinities. Nash-Sutcliffe model efficiency, NSE, is a model evaluation criterion proposed by Nash and Sutcliffe (1970) [27]. As shown in Table 4, the Nash–Sutcliffe model efficiency for the calibration period is 0.63 while for the validation period is 0.43. This indicates the model efficiency is acceptable for the calibration period than the validation period. However, the model performed similarly in terms of errors, including Root mean squared error (RMSE), Mean Absolute Error (MAE), Relative Root Mean Squared Error (RRE), indicating that the model suitable for both calibration and validation period.

The model underestimates the higher inflows than the observed at the Wulabo Reservoir. This may be because runoffs from local arroyos, particularly two seasonal streams (East Baiyang and West Baiyang Rivers) are not incorporated in the simulations, as there is no runoff data available. To better simulate impacts of local storm events on the river flow as well as the potential release of flood flow using irrigation networks, it is recommended that the local arroyos be evaluated, and its runoff events are considered in the enhancement of the model configuration in the future study in the basin. In general, the model construction is promising by capturing major features in the system and producing well-simulated inflow to the Wulabo Reservoir. Results indicate that the RiverWare model captured key features and showed a high correlation between the simulated flow and historic observations, and can be used for water operation management under different scenarios.

Table 4. Statistical measures for calibration and validation periods of the RiverWare Model

Measures	Calibration Period	Validation Period
Coefficient of Determination (R^2)	0.66	0.49
Nash–Sutcliffe model efficiency (NSE)	0.63	0.43
Root mean squared error (RMSE), $10^6 m^3$	0.25	0.23
Mean Absolute Error (MAE), $10^6 m^3$	0.15	0.14
Relative Root Mean Squared Error (RRE)	0.03	0.06

4.2. Scenario Analysis

4.2.1. Generated daily flow for different scenarios

A developed snowmelt runoff model upstream from the Yingxiongqiao gaging station [20] was used to generate daily runoff for spring and summer seasons at Yingxiongqiao gaging station based on the designed scenarios. The generated daily runoff was used as input to the RiverWare model. The RiverWare model was then used to assess alternative water management strategies including daily water operation at the irrigation districts by considering the conjunctive use of surface water and groundwater resources. As shown in Table 3, three scenarios were considered in the study: Baseline condition (Average of 2005-2007), Reduced precipitation (upper basin average precipitation reduced by 30%), Increased temperature (upper basin average temperature increased by 2.5℃). The baseline flow is considered as the average flow and weather conditions from 2005 to 2007. The Reduced Prep scenario is the precipitation in the upper basin decreased by 30% as compared to baseline year, and the Increased Temp scenario is considered as the temperature in the upper basin is increased by 2.5 ℃ and evapotranspiration is also increased by 8% respectively as compared to the baseline year. The calibrated daily rule-based simulation RiverWare model was used to simulate water management operation policies at the lower valley of the study area under different scenarios.

The precipitation and temperature changes in the upstream mountainous area have significant impacts on the streamflow at the mountain outlet as measured at Yingxiongqiao gaging station. Figure 7 illustrates generated daily spring-summer (March-August) runoff at Yingxiongqiao gaging station under different scenarios. As can be seen from Figure7, the runoff changes significantly as the precipitation in the upper basin changes. Particularly, the magnitudes of summer precipitation change affect summer runoff mostly. However, the precipitation has an insignificant effect on the timing of streamflow. Similarly, the effect of temperature on spring-summer runoff is significant. As the temperature rises, the more runoff occurs in the spring; this is because the Urumqi River is the snow-dominated watershed where most of its runoff comes from the snowmelt, the increased spring runoff is large because of the increase of temperature in the basin. The generated daily runoff at Yingxiongqiao gaging station was used as the input to the daily rule-based RiverWare model to provide water operation policies at the lower valley irrigation district.

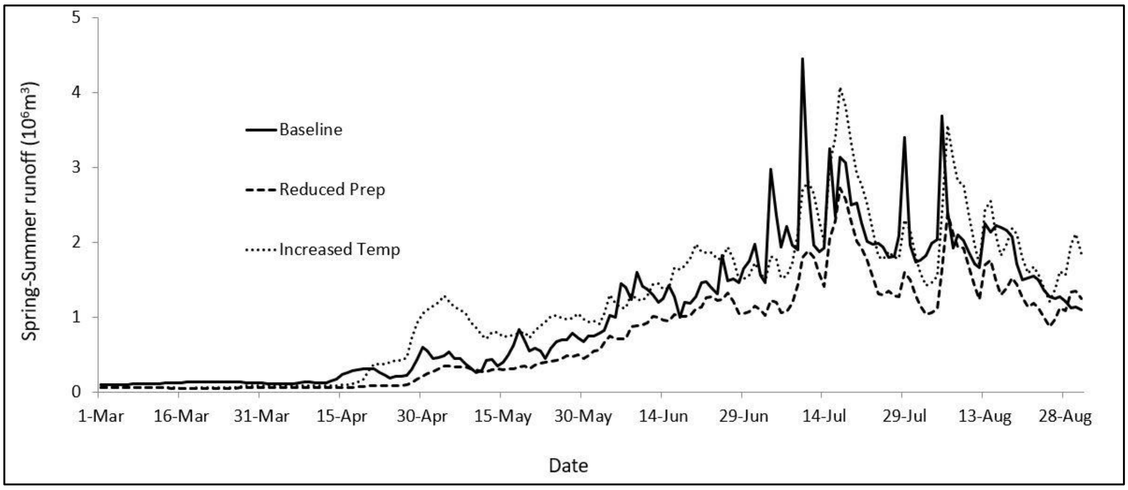

Figure 7. Generated daily spring-summer (March-August) runoff at Yingxiongqiao Gaging Station under different scenarios

4.2.2. Surface Water Diversion

The functional relationships between diversions at Huangcaoliangzi canal, Gongsheng canal and Qingnian canal diversion points and river flow in the main river channel based on laws and regulations in the districts were considered and defined in RiverWare model by writing rules in RiveWare Policy Language (RPL) and incorporation of them into the model. According to the water allocation policies that regulated for decades by the water management bureau of the county, the number of diversions is determined by the water amount in the river. For example, as the largest water user in the area, the diversions to Qingnian Irrigation District is proportional diversion based on the runoff in the river on a year. As indicated in Figure 8, the daily diverted flow from the river to Qingnian irrigation district follows the same pattern and magnitude as in the spring-summer daily flow under different scenarios. The more water in the river, the more diversions occur at the Qingnian diversion dam. During the reduced precipitation scenario, the diversion at the Qingnian diversion was reduced significantly as compared to other scenarios due to reduced flow in the river.

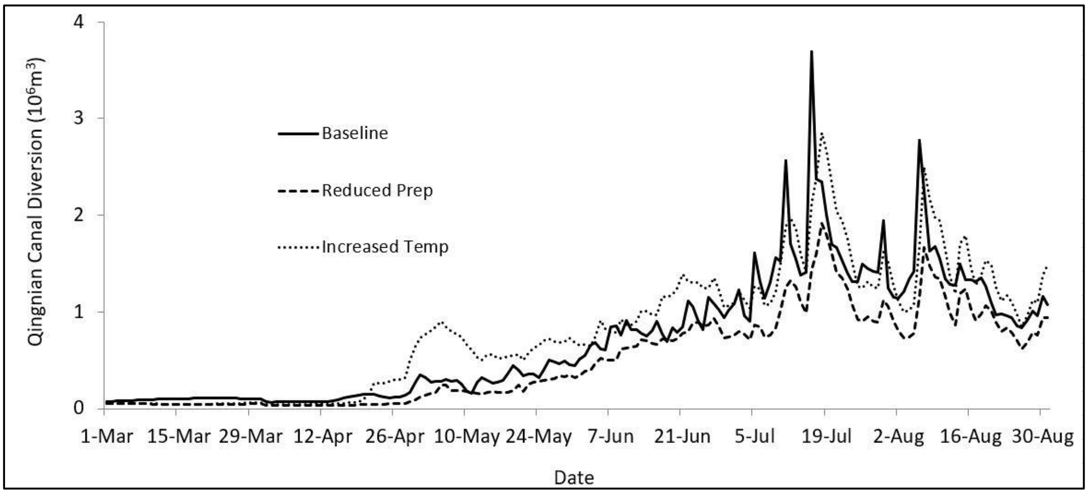

Figure 8. Simulated daily diversions at Qingnian diversion dam during the spring-summer season under different scenarios

4.2.3. Conjunctive Uses of Surface Water and Groundwater

The conjunctive use of the surface water and groundwater in irrigation districts are evaluated based on the simulation results from the RiverWare model that run from March to August under different scenarios. For brevity, some results in the Qingnian irrigation district are presented in this paper. The daily canal diversions and groundwater pumping under different climate scenarios for the Qingnian irrigation districts are shown in Figure 9. As can be seen, groundwater is used to supplement surface water to cope with the irrigation demands to meet the deficits in irrigation season. In the baseline flow scenario, the groundwater pumping occurs mostly in the spring and early summer (March to middle July) due to lack of surface water in the river. After July, as the temperature rises, the snowmelt runoffs start to add up the surface water in the river, and consequently, there is enough surface water for irrigation during the summer, no need for groundwater pumping in the summer almost all the time. In reduced precipitation scenario, the reduced precipitation resulted in the reduced runoff, and more groundwater pumping occurs for irrigation both in the spring and summer. Due to not enough surface water can meet crop water requirements in spring and summer; more groundwater pumping is required to meet irrigation needs. In increased temperature scenario, the impact of temperature on surface runoff is significant in the basin, and more snowmelt water occurs at the end of spring compared to other scenarios. Because the increased temperature induces the increased crop evapotranspiration, the water demand in the irrigation district increases. This will require more groundwater pumping even there is more water in the river. Hence the whole pattern of conjunctive use of surface water and groundwater under increased temperature scenario is similar to the baseline scenario, except there is less groundwater pumping during spring than surface water diversion.

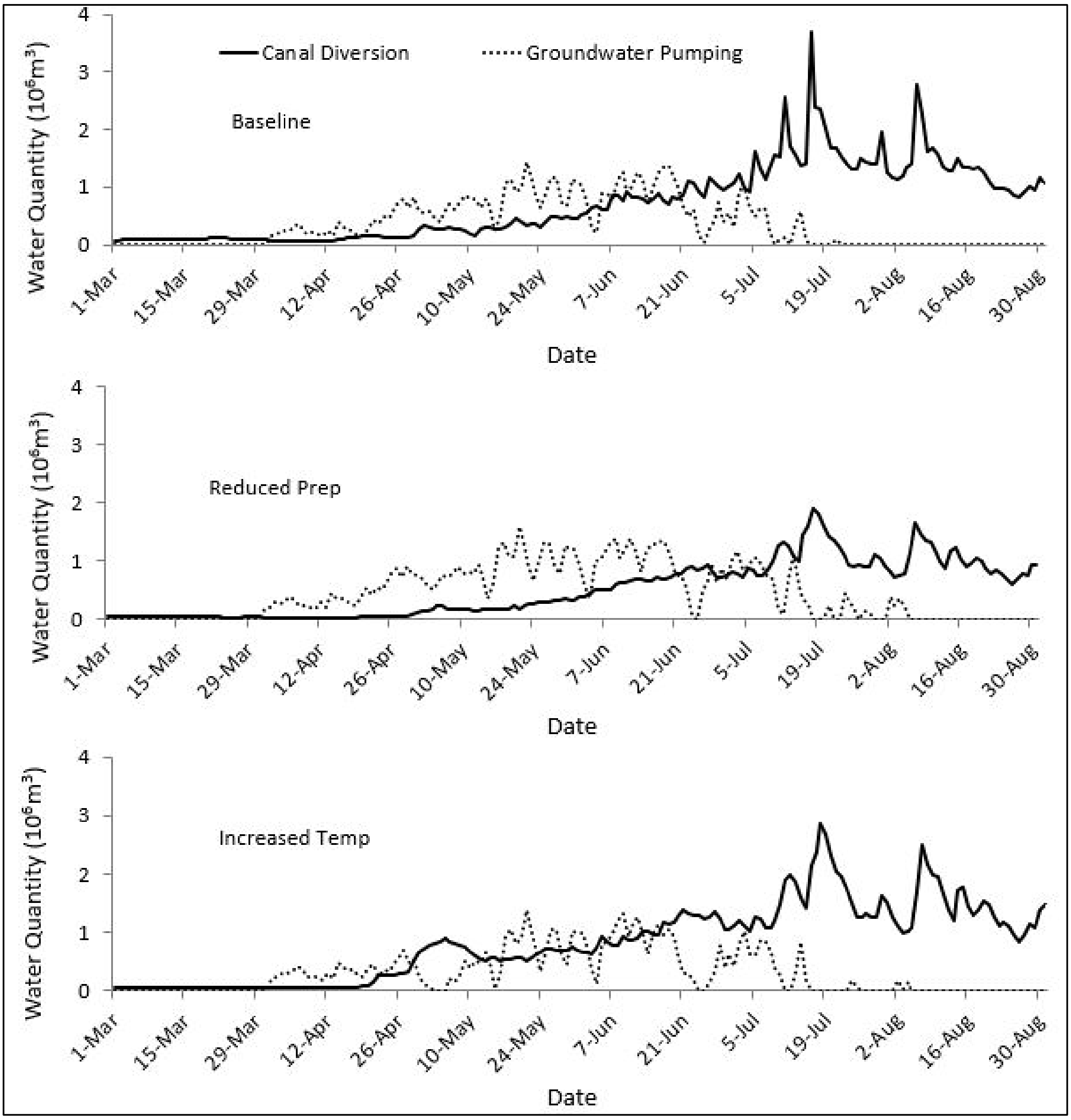

Figure 9. Surface water and groundwater conjunctive use for Qingnian Canal Irrigation District under different scenarios

4.2.4. Discharge into the Wulabo Reservoir

Wulabo Reservoir inflow changes under different flow scenarios. As can be seen from Figure 10, the impact of increased temperature on the reservoir inflow is not significant as compared to baseline scenario in spring and early summer. The August inflow tends to increase as compared to baseline since the higher temperature induces more snowmelt runoff during the summer when the temperature hits high. On the contrary, the reduced precipitation results in reduced reservoir inflow both in spring and summer, since most of the surface runoff is used to meet upstream irrigation and other water use needs, consequently less water comes into the reservoir. When it compared the impact of precipitation and temperature on the reservoir inflow, it seems that the reduced precipitation results considerable runoff reduction and inflow reduction to the reservoir.

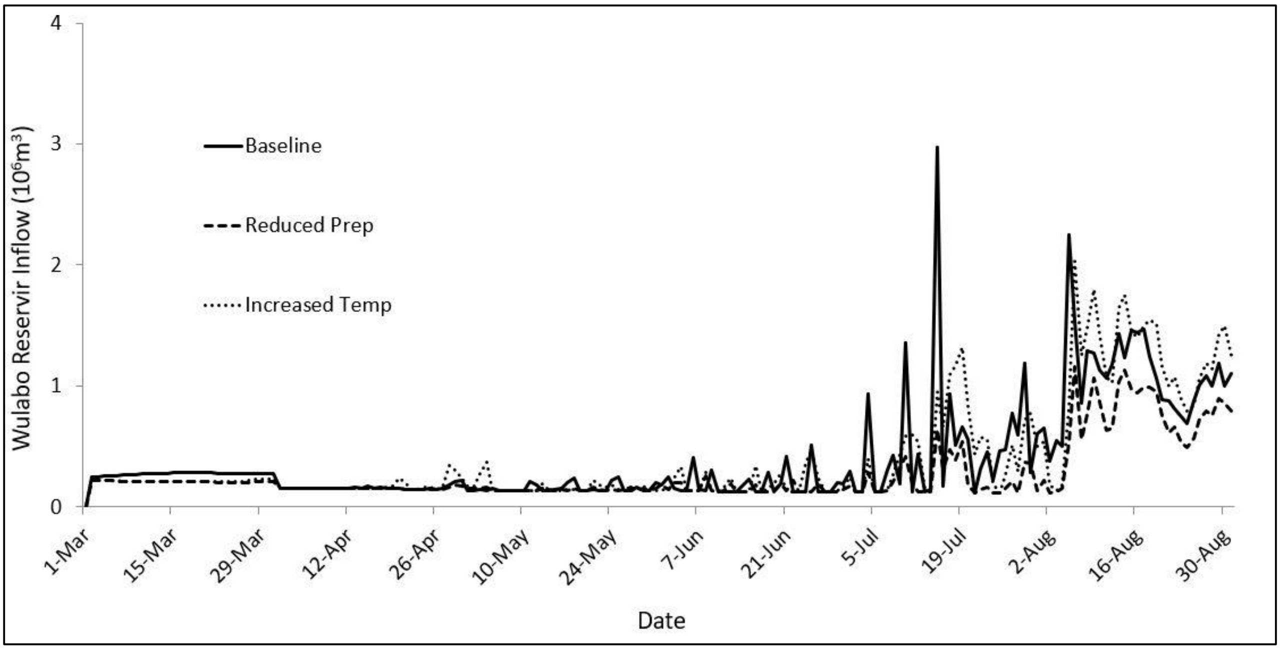

Figure 10. Simulated daily Wulabo Reservoir inflow during the spring-summer season under different scenarios

As indicated in Table 5, 30% reduction in average precipitation in the upper basin (as in Reduced Precipitation scenario), resulting in over 30% reduction to the spring-summer total inflow of the Wulabo Reservoir from March 1st to August 31st in a year. In contrary, the impact of temperature changes (Increased temperature scenario) is not as significant as precipitation regarding the magnitude of inflow changes. The 2.5 ℃ increases on average upper basin temperature, resulting in 0.6% increases to the spring-summer total inflow of the Wulabo Reservoir from March 1st to August 31st in a year. This indicates that complex hydrological impacts of temperature increase in this snowmelt-dominated basin. Although higher the temperature indices more snowmelt runoff, it also increases crop water demand and other evaporative losses from water surfaces of canals, river, ponds, which in turn offset the water budget in the study basin.

Table 5. Spring-summer Wulabo Reservoir total inflow volume at different scenarios (10^6 m^3)

Scenarios	Baseline	Reduced Prep	Increased Temp
Spring-Summer Inflow (10^6 m^3)	72.9	49.4	73.4
Changes in Inflow (%)	0.0	-32.3	0.6

5. Conclusion

Because of the frequent occurrence of drought and growing water demand in arid regions of the world, the river alone could no longer meet the regional water needs, leading to increased groundwater extraction and dropping groundwater tables. A better understanding of the conjunctive water uses crucial in sustainable water management. In this study, daily rule-based RiverWare models were developed for the agricultural watershed of Urumqi River, Xinjiang, China. This was the very first attempt to use the RiverWare model to simulate groundwater and surface water conjunctive use under different drought scenarios in China's dry west mountainous watershed where the snowmelt is the dominant source of water.

The model has successfully captured the complex hydrological process in the study area using multiple groundwater objects (GWOs), seepage losses from the canals and the river, groundwater pumping, and returns flow. The river reaches were divided based on the length of reach and shape of river reach, as well as locations of gaging stations. The conjunctive use of groundwater and surface water was further evaluated for irrigation districts in the study area under different drought scenarios by linking the predictions of snowmelt runoff models (SRM) into the developed RiverWare models in the basin. The results from the research suggested that the RiverWare model has the advantages of simulating river and reservoir operations, groundwater and surface water conjunctive use in the irrigation area and is more suitable to the complicated agricultural land that located in the lower basin of the river. The RiverWare models adequately reproduced the historic reservoir inflows for the Wulabo Reservoir with acceptable flexibility and accuracy. In general, the water allocation policies from RiverWare models' outcome provide guidelines for conjunctive uses of groundwater and surface water resources within the basin under different water supply scenarios in the future.

The design and configuration of the RiverWare model in this study are based on the availability of representative data on the relevant physical features of the irrigation system, GIS data, and some onsite measurements. The model underestimates the higher inflows than the observed at the Wulabo Reservoir. This may be because runoffs from local arroyos, particularly two seasonal streams (East Baiyang and West Baiyang Rivers) are not incorporated in the simulations, as there is no runoff data available. To better simulate impacts of local storm events on the river flow as well as the potential release of flood flow using irrigation networks, it is recommended that the local arroyos be evaluated, and its runoff events are considered in the enhancement of the model configuration in the future study in the basin. Water demand estimates for crop water consumptive uses was hindered by lack of historical crop acreage and crop pattern data. By accessing and incorporating detailed historic crop acreage data as well as local crop coefficients, it is anticipated to generate more accurate water demand estimation in the future studies in the basin.

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