water

MDPI

Article

Evaluating Water Supply Risk in the Middle and Lower Reaches of Hanjiang River Basin Based on an Integrated Optimal Water Resources Allocation Model

Xingjun Hong [1], Shenglian Guo [1,*], Le Wang [1], Guang Yang [1], Dedi Liu [1], Haijin Guo [2] and Jun Wang [2]

[1] State Key Laboratory of Water Resources and Hydropower Engineering Science, Hubei Collaborative Innovation Center for Water Resources Security, Wuhan University, Wuhan 430072, China; hongxingjun@whu.edu.cn (X.H.); lewangwhu@126.com (L.W.); yang_guang@whu.edu.cn (G.Y.); dediliu@whu.edu.cn (D.L.)
[2] Bureau of Hydrology, Changjiang Water Resources Commission, Wuhan 430010, China; guohj@cjh.com.cn (H.G.); wangj@cjh.com.cn (J.W.)
* Correspondence: slguo@whu.edu.cn; Tel./Fax: +86-27-6877-3568

Academic Editors: Y. Jun Xu, Guangxin Zhang and Hongyan Li
Received: 30 June 2016; Accepted: 17 August 2016; Published: 24 August 2016

Abstract: The rapid socio-economic development and expanding human-induced hydrological alteration have strengthened the interactions between the social and hydrologic systems. To assess regional water supply security under changing water supply and demand condition in strongly human-impacted area, an integrated water resources management model that fully incorporates water demand prediction, optimal water resources allocation and water supply risk analysis is proposed and applied in the mid-lower reach of Hanjiang River basin. The model is run under three scenarios considering increasing water demand and expanding water diversion projects, and then spatial and temporal distributions of water supply reliability and vulnerability are evaluated. Results show that water supply risk in the mid-lower reach of Hanjiang River basin, especially units that take water directly from the mainstream, will be gradually enlarged in the future due to the expansions of both water demand and inter-basin water diversion capacity. The proposed method provides a practical approach towards more robust decision-making of long-term water resources planning and management under changing environment.

Keywords: water resources; optimal allocation model; water supply risk; reliability; vulnerability; water diversion projects; Hanjiang River basin

1. Introduction

Water resources serve irreplaceable functions in human society and ecosystems. With the rapid social and economic development, ever-growing anthropogenic interventions to the hydrologic cycle have significantly strengthened the interaction between social and hydrologic systems [1,2]. Over the last decades, it is well recognized that both domestic and productive water demand in most watersheds have been dramatically increased due to rapid population growth, along with accelerating agricultural and industrial expansions, all of which have led to intensifying competition and conflicts among different water use sectors [3,4].

In addition to consuming more freshwater, human activities have also exerted large-scale impacts on the hydrologic systems either directly or indirectly. For instance, direct withdrawals of water from natural aquatic systems to satisfy domestic and productive demands have led to lack of water for environment and thus jeopardize ecosystem health [2]. In addition, human-induced land use and land cover changes as well as direct flow regulation, e.g., dam construction and inter-basin water diversion, have further distorted the natural flow regimes. Besides, human activities can impact water resources in an indirect and long-term way, most of which are related to climate change through greenhouse gas emissions [1]. The recently released Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) declared that climate change will significantly impact the availability, seasonality, and extreme properties of natural water resources [5]. Global warming is supposed to cause more intense and frequent extreme events, e.g., floods and droughts, due to the increase in hydrologic variability [6,7]. Among various extreme events, droughts are likely to substantially reduce water supplies and deteriorate water qualities [8]. In turn, the potentially altered hydrological regimes will present added challenges to water managers who have already suffered from strong inter-annual variability of observed water resources [9,10].

To confront the growing threat of failures for water resources systems to meet water requirements, some countries have managed to either propose executable administrative measures or improve existing water distribution systems. However, political and engineering measures including limiting the water use quotas allocated to different water users [11,12], as well as improving the efficiency of water usage by minimizing the leakage loss of water distribution networks [13,14] can reduce water consumption to some extent, but may be insufficient to alleviate the water stress. Reservoirs are among the most efficient man-made infrastructures for managing water supply and reducing the devastating impacts of droughts [15]. The mass constructions and improving operation skills of basin-scale reservoir and water distribution network systems have provided resilience for water supply against extremes, which in turn promoted the development and application of water resources allocation models.

Some simulation-based platforms for water resources management have been developed to simulate water supply with routine reservoir operation rules and pre-set water user priorities. For example, the Aquatool model [16], developed by the Universidad Politecnica de Valencia, has been used by two river basin agencies in Spain as a standard decision-support tool to develop their Basin Hydrological Plans. Another water supply simulation package, the Resource Allocation Model (REALM) [17], has been used to model two case studies in Australia covering both urban and rural water supply systems with diverse forms of operating rules. The Water Evaluation and Planning model (WEAP) [18] model, developed by the Stockholm Environment Institute, incorporates watershed-scale hydrologic processes with water management model by introducing the concept of demand priorities and supply preferences. The Mike Basin model [19] developed by the Danish Hydraulic Institute, has been widely used by water agencies to simulate basin-scale water resources management for multi-purpose, multiple-reservoir systems by specifying associated reservoir operation rule curves and guiding water extraction from several reservoirs in order of priority. Despite their rich modules and user-friendly interfaces, the simplified reservoir operation rules and water allocation strategies of these models operated within a "what-if-then" scenario-based framework generally offer poor flexibility if changing hydro-climatic and anthropogenic factors are considered.

Motivated by abovementioned shortcomings, this paper aims to develop an integrated optimal water resources allocation model for regional water supply security analysis under changing environment in strongly human-impacted area. Optimal water allocation models have been earlier applied in agricultural area to optimize water irrigated to different crops, especially under deficit irrigation [20,21]. With the improvement of living standard and the expansion of industry, water allocation has to gradually take into account multiple objectives involving social, economic, environmental and political tasks [22,23]. As a result, a variety of multi-objectives algorithms such as the macro-evolutionary genetic algorithm [24], the non-dominated sorting genetic algorithm [25], the macro-evolutionary multi-objective immune algorithm [26], etc. have been proposed and applied to achieve water allocation policies that are economically efficient, technically feasible as well as socially fairly in recent years. Zhou and Guo [27] and Yang et al. [28] derived adaptive multi-objective operating rules for the Danjiangkou reservoir in China to increase the ecological flow and water supply yield, respectively. Zhou et al. [29,30] proposed a theoretical framework for optimal multi-objective allocation for a complex adaptive water resources system and applied it to the water resources planning of Dongjiang River basin.

Subsequently, water allocation models have been incorporated in the water supply risks analysis using the reliability and resilience criteria proposed by Hashimoto et al. [31] to evaluate regional socio-economic drought conditions [32] or the drought mitigation abilities of local water supply systems [33,34]. Rajagopalan et al. [35] assessed the annual risk of the Colorado River water supply and suggested flexible management practices to mitigate the increased risk due to future reduction in flows. Milano et al. [36] develop a synthetic modeling framework driven by a conceptual GR2M hydrological model and a storage dam model to evaluate current and future capacity of water resources to meet different water demands. However, in regions where water resources have been excessively overexploited and overused, the building-up pressure of water demand in the future will impose an added vulnerability to local water supply system, causing societal, economic and environmental damages [37]. Moreover, while most current studies emphasize great importance on the impact of climate change on local water resources planning, few of them argue the effects of large-scale inter-basin water diversion projects on the water resources area, especially on the lower reach of the water intake after water diversion in the upstream.

The rest of this paper is organized as follows: in Section 2, a brief introduction of study area and dataset are presented, followed by the methods used in this study in Section 3. Then, results are shown in Section 4. Conclusions and discussion is drawn in Section 5.

2. Study Region and Data

2.1. Hanjiang River Basin

The Hanjiang River is located between 106° E–114° E and 30° N–34° N with a length of 1577 km and a drainage area of 159,000 km^2 (Figure 1). The mainstream of the river originates from the southern slope of the Qinling Mountains, then passes through several provinces in central China, finally pours into the Yangtze River at Wuhan City. The whole basin is divided into an upper and a mid-lower reach by the Danjiangkou reservoir (Figure 1). The sub-tropical monsoon climate and the varying topography result in dramatic spatio-temporal diversity of water resources distribution.

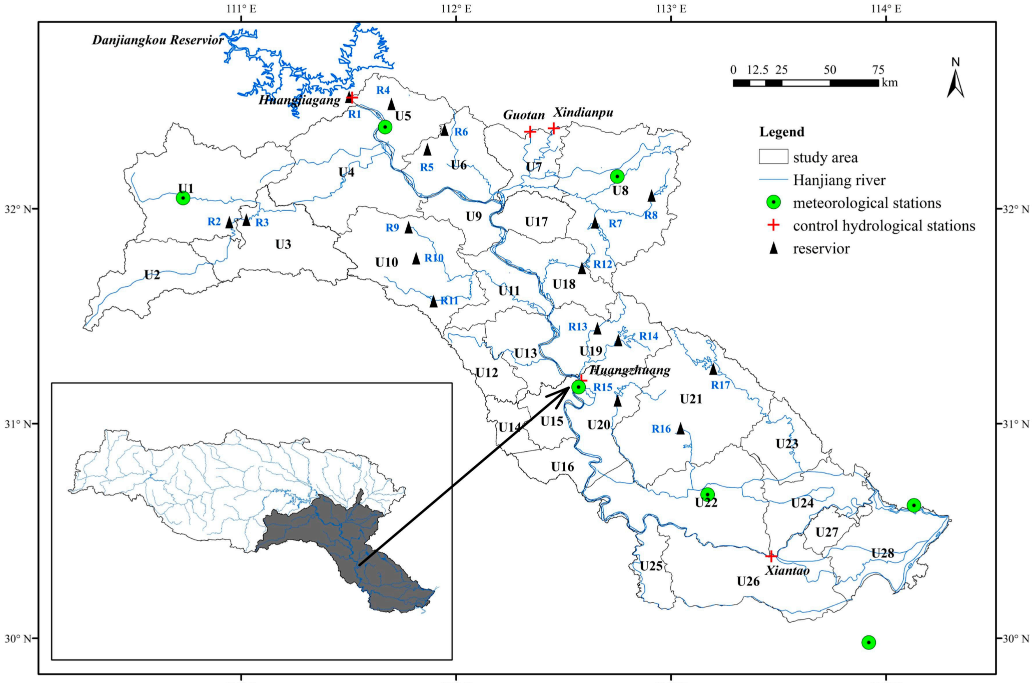


Figure 1. Location and hydrological stations in the Hanjiang River basin.

Despite its relative abundance in water resources with mean annual precipitation ranging from 700 mm to 1800 mm, the Hanjiang River basin has long suffered from extremely uneven distribution of annual rainfall and runoff between flood and non-flood season, along with increasing water stress due to rapid population growth and accelerating economic expansion. Moreover, there have been several studies revealing a very dry period since 1990s [38] and a decreasing trend of precipitation in the near future over the upper basin is also detected [39].

2.2. Water Diversion Projects

As an important engineering measure to mitigate the unevenness of water resources distribution, inter-basin water diversion projects have long been used to solve water shortage problem in the water-receiving areas. The Hanjiang River has been serving or planned as the water source of several intra-and inter-basin water diversion projects, including the middle route of the South-to-North Water Diversion Project (SNWDP), Qingquangou Water Diversion Project (QWDP) from Danjiangkou reservoir to Northern Hubei Province, and Han-to-Wei Water Diversion Project (HWWDP) from Hanjiang River to Weihe River.

The water diversion projects and designed annual mean transfer water are shown in Table 1. The current design annual mean transfer water from the Danjiangkou reservoir through SNWDP and QWDP is 600 and 628 million m^3, respectively. It should be noted that the present transfer water is diverted to the Tangbai River basin and the northern Hubei Province, both of which are mainly located within the Hanjiang River basin.

Table 1. Information of water diversion projects located in the Hanjiang River basin.

No.	**Name**	**Water Source**	**Water Receiving Area**	**Designed Annual Mean Transfer Water (Total/Inter-Basin)**		
				Present	**Short-Term**	**Long-Term**
				(million m^3·year^{-1})	**(million m^3·year^{-1})**	**(million m^3·year^{-1})**
1	SNWDP	Danjiangkou Reservoir	Tangbai River Basin [1] and Huang-Huai-Hai Plain	600/0	9500/8500	13,100/12,050
2	QWDP	Danjiangkou Reservoir	Northern Hubei Province	628/0	628/0	1398/291
3	HWWDP	Huangjinxia and Sanhekou Reservoir [2]	Weihe River Basin	0/0	1000/1000	1500/1500

Notes: [1] The Tangbai River is a tributary of Hanjiang River basin; [2] Both Huangjinxia and Sanhekou reservoirs are located in the upstream of Danjiangkou reservoir, thus the transferred water should be removed first when estimating the inflow to the Danjiangkou reservoir.

According to the Integrated Water Resources Planning of Hanjiang River Basin, for the short-term planning period, water transferred through SNWDP will increase by 8900 million m^3 along with newly added 1000 million m^3 upstream the Danjiangkou reservoir through the HWWDP, while, for the long-term planning, the capacity of water diversion through SNWDP and HWWDP will become 13,100 and 1500 million m^3, respectively. Meanwhile, more water volume is supposed to be removed through QWDP with design mean annual water transfer amount of 770 million m^3 to improve the water supply reliability in the whole northern Hubei Province. However, with part of the newly diverted water from QWDP being transferred outside the Hanjiang River basin (about 290 million m^3), it may increase water supply risk in the downstream of water source areas.

2.3. Study Area

Transferring part of water outside the water source area is likely to aggravate the water scarcity within the basin, especially in the lower reach of the water intake. Gu et al. [40] declared that water supply risks in the planning year 2015 and 2030 will be gradually increased in the middle and lower Hanjiang River basin after diverting 9500 million m^3 of water from the Danjiangkou reservoir. However, the previous study treated the whole middle and lower Hanjiang River basin as a single water user and did not provide a spatial distribution of water supply risk.

Therefore, an attempt is undertaken to evaluate the ability of the river and reservoir system in the mid-lower reach of Hanjiang River basin (MLHRB) to satisfy water demands in finer spatial resolution over some planning horizons after water diversion. It should be noted that, the term MLHRB in this paper only covers the mid-lower Hanjiang River sub-basin within the Hubei Province while neglecting the part belonging to the upstream Henan Province. Instead, the discharge from Henan is treated as inflow to the study area controlled by two hydrological stations (Guotan and Xindianpu, Figure 1) located in the very border between these two provinces.

To construct the optimal allocation model of water resources, the water network of MLHRB is divided into 28 units and depicted in Figure 2 according to intersections of both watershed and administrative county regions. Only 17 existing large reservoirs were encompassed and information of these reservoirs is listed in Table 2.

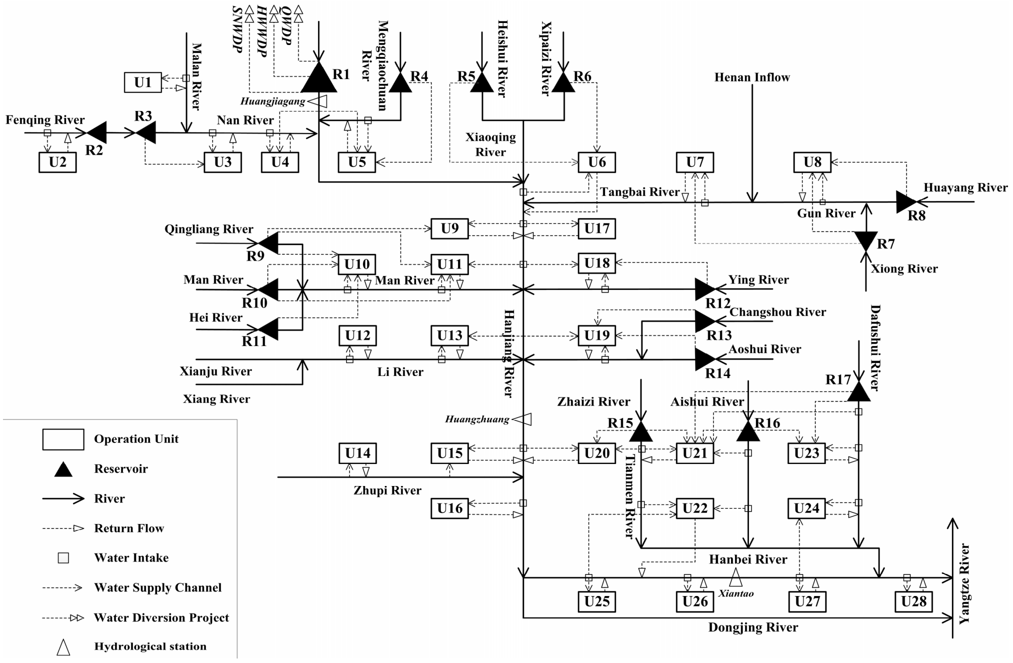


Figure 2. The water network of the mid-lower reach of Hanjiang River basin (MLHRB).

2.4. Data

Historical discharge records of the outlet of each operation unit and the inflows of reservoirs during 1956–2010 were collected from the hydrological almanacs compiled by the Bureau of Hydrology, Changjiang (Yangtze) Water Resources Commission. Observed precipitation series of seven national meteorological gauging stations (see Figure 1) were downloaded from National Meteorological Database [41]. The closest meteorological station to an operation unit is chosen to represent the natural water resources abundance of that unit for each year. The basic characteristics, operation rules and downstream river ecological demands of 17 reservoirs were extracted from the Dispatching Schedules of Hubei Provincial Large Reservoirs compiled by Hubei Provincial Department of Water Resources [42].

Water demand scenarios, water consumption ratios, social and economic development projection for each unit in the base year (2010) and two planning horizons, i.e., short- and long-term periods, were extracted from the report of Integrated Water Resources Planning of Hanjiang River Basin compiled by the Changjiang Water Resources Commission that is the official administrative organization for water resources planning and management of the Changjiang River basin.

Table 2. Characteristics of reservoirs located in the middle and lower reaches of Hanjiang River basin.

No.	**Reservoir**	**Total Storage**	**Normal Pool Water Level**	**Useful Storage**	**Flood Limited Water Level**			**Dead Water Level**
					Pre-Flood Season	**Main Flood Season**	**Post-Flood Season**	
		(million m^3)	**(m)**	**(million m^3)**	**(m)**	**(m)**	**(m)**	**(m)**
R1	Danjiangkou	33,910	170.00	29,050	-	160.00	163.50	150.00
R2	Sanliping	499.00	416.00	211.00	-	403.00	412.00	392.00
R3	Siping	269.00	315.00	145.00	313.86	313.86	313.86	294.00
R4	Mengqiaochuan	110.33	143.00	88.15	142.20	142.20	142.20	126.00
R5	Hongshuihe	103.60	117.00	58.90	117.00	117.00	117.00	109.00
R6	Xipaizihe	220.40	111.80	22.00	111.80	111.80	111.80	100.00
R7	Xionghe	195.90	125.00	115.90	125.00	125.00	125.00	113.00
R8	Huayanghe	107.00	144.19	70.80	144.19	144.19	144.19	128.69
R9	Shimenji	154.03	195.00	114.69	195.00	195.00	195.00	158.00
R10	Sandaohe	154.60	154.00	127.42	154.00	152.40	153.00	112.70
R11	Yuntaishan	123.00	164.50	89.00	163.00	163.00	163.00	126.89
R12	Yinghe	121.66	132.70	76.31	132.70	132.70	132.70	116.20
R13	Huangpo	125.61	77.50	70.25	76.00	76.00	76.00	65.50
R14	Wenxiakou	520.00	107.00	269.00	105.00	105.00	105.00	95.00
R15	Shimen	159.10	91.00	68.60	91.00	91.00	91.00	80.00
R16	Huiting	313.40	84.75	173.50	84.75	84.75	84.75	73.00
R17	Gaoguan	201.08	121.50	154.32	119.00	118.00	119.00	100.50

3. Methodology

The framework that we propose to evaluate the water supply risk is shown in Figure 3. Through the comparisons of water satisfaction or deficiency in different water users and regions between present and planning scenarios, the impacts of social development and water transfer on regional water supply could be assessed. The proposed integrated water resources management model to evaluate the water supply risk consists of three modules: (1) a water demand projection module to forecast future water requirement scenarios; (2) a water management module to simulate the reservoir operation and water allocation under different scenarios; and (3) a water supply risk evaluation module to assess the magnitude of water shortages. The details of these modules are described as follows.

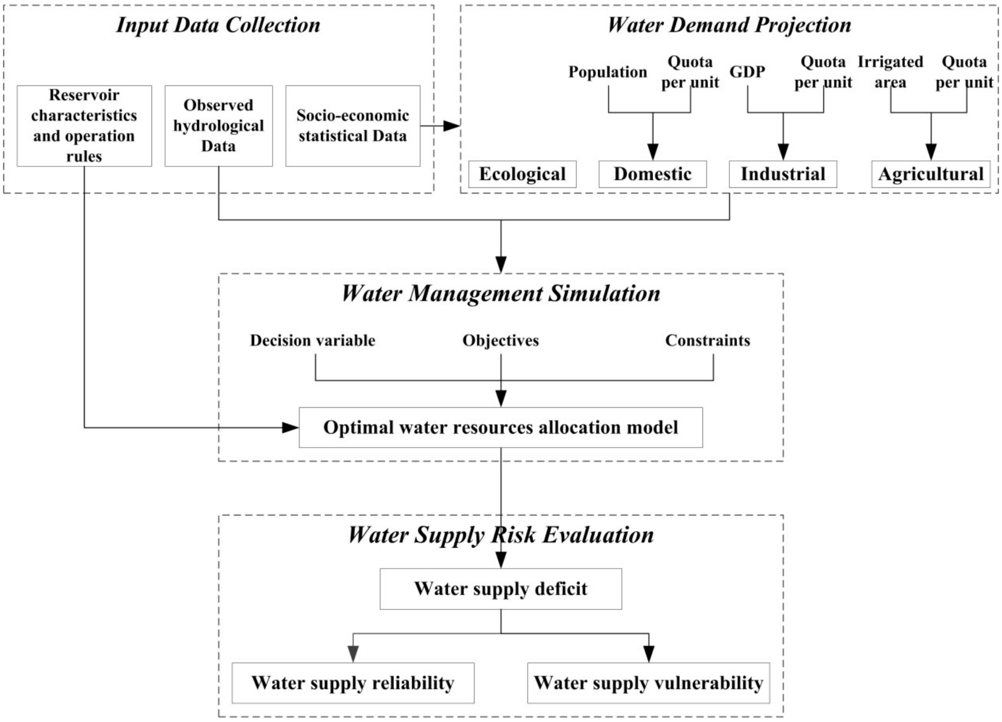


Figure 3. Structure of the integrated water resources management model.

3.1. Water Demand Projection Module

There are totally five types of water users to be considered in this study, i.e., urban domestic water user WU_1, rural domestic water user WU_2, industrial water user WU_3, agricultural water user WU_4 and in-stream ecological water user WU_5. The quota method, or what Brekke et al. [43] terms “unit water demand analysis”, is used to estimate the annual water demand in domestic and productive sectors for different period:

$$WD_{i,j} = q_{i,j} \times A_{i,j},\ j = 1, 2, 3, 4 \tag{1}$$

where $WD_{i,j}$ is the water demand of the *j*th sector ($j = 1, 2, 3, 4$) in the *i*th operational zone for a specific year. $q_{i,j}$ is the prearranged consumption quota per unit of each water demand category, e.g., per capita water consumption, water consumption per ten thousand Yuan of Gross Domestic Product (GDP) of industry, synthetically net irrigation water requirement per unit area, etc., which are estimated based on the future economic development, local water restriction and water policies. Specifically, the agricultural quota is related to the annual effective precipitation of several typical exceedance frequencies, defined as P = 50%, 75%, 90% and 95% in this study. The higher frequency the annual precipitation has, the drier the year is, and the more supplementary water drawn from the river or reservoirs is needed. If the exceedance frequency of annual effective precipitation is less than

50% or higher than 95%, then the agricultural water demand under P = 50% or P = 95% is adopted, respectively. The actual agricultural water demand with 50% < P < 95% is estimated by interpolation between typical water demand levels. Correspondingly, $A_{i,j}$ is the number of water units belonging to each water use sectors, e.g., projected urban and rural population, estimated industrial GDP, effective irrigated area taken from the economic and social development plan of the study area, etc.

The in-stream ecological water demand (WD_5) is the amount of water needed for a healthy in-stream environment to support the survival of aquatic wildlife and satisfy other ecological use. In this paper, the Tennant method [44] is applied to estimate the in-stream ecological flow for each zone by taking the product of the annual average runoff for the ith operational zone and the minimum required proportion of runoff in the flood season or non-flood season, respectively.

After determining the annual water demand for each water users, the distribution of monthly water requirement throughout the year in each sector can be obtained by multiplying the ratio of monthly water use to the annual water demand.

3.2. Water Management Simulation Module

An optimal allocation model of available water resources is developed to calculate the regional theoretical water supply ability to meet water demand of each unit. The amount of available water can be obtained through a joint operation of river and reservoir system. Generally, water in the river channel, usually the local water yield and upstream remaining water inflow to the unit, is firstly used to satisfy different water users and the water levels of upstream reservoirs are kept at the upper limits to store as much water as possible. If water in the river is not sufficient for the total demand, water should be taken from the reservoir storage. Water supplied to each water user is according to its demand when there is enough available water. Otherwise, water is allocated among various users based on an optimal water resources allocation model as below.

3.2.1. Objective Function

The objection of the optimal water resources allocation is to minimize the weighted total shortage of different water users in different units:

$$OF = \min\left[\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{5}\omega_{i,j}\left(WD_{i,j}^{t} - x_{i,j}^{t}\right)\right] \tag{2}$$

where t is the monthly time step, T is the total allocation period, I is the number of operation zones, and j is the number of water users. $WD_{i,j}^{t}$ and $x_{i,j}^{t}$ are the monthly water demand and supply of the jth sector in the ith operational zone, respectively. $\omega_{i,j}$ is the weight of shortage of the jth sector in the ith zone representing the priority of water supply preference estimated via dividing the net economic benefit of water supplied to the sector by the total net economic benefit of all sectors to ensure that $\sum_{i=1}^{I}\sum_{j=1}^{5}\omega_{i,j} = 1$. The net economic benefits of off-stream water supplies are calculated as the water use benefit minus water supply cost [22]. The net economic benefits of domestic water supplies (either urban or rural) are higher than those of the industrial and agricultural sectors. It should be noted that the weight of ecological water deficit is difficult to estimate but should be set high because the health of ecology is essential to the stability and sustainability of the society. In this paper, the net economic benefit of ecological water supply is taken as the average of all other sectors. Therefore, the values of $\omega_{i,1} > \omega_{i,2} > \omega_{i,5} > \omega_{i,3} > \omega_{i,4}$.

3.2.2. Constraints

(1) Water availability constraint:

$$\sum_{j=1}^{5}x_{i,j}^{t} \le AW_{i}^{t} \tag{3}$$

where AW_{i}^{t} is the available water in the ith operational zone in time step t.

(2) Water demand constraint:

$$\eta_{\min,j} WD_{i,j}^{t} \leq x_{i,j}^{t} \leq WD_{i,j}^{t} \tag{4}$$

where $0 < \eta_{\min,j} \leq 1$ ($j = 1, 2, 3, 4, 5$) is the minimum required percentage of water demand of the jth water sector if AW_i^t is higher than $\left(\sum_{j=1}^{5} \eta_{\min,j} WD_{i,j}^{t}\right)$. $\eta_{\min,j}$ is adjusted based on the tolerance of public for the shortage occurred in this sector. For example, the living condition of people should be kept safe, thus $\eta_{\min,1}$ and $\eta_{\min,2}$ are both nearly equal to 1. While the agricultural production activities can be adjusted easily according to the water available, therefore the $\eta_{\min,4}$ can be set relatively low. The tolerability of in-stream ecological water demand is also relatively high because when living and productivity are seriously threatened, the in-stream ecological water is supposed to be extracted to temporally alleviate the water scarcity. Usually, $\eta_{\min,1} > \eta_{\min,2} > \eta_{\min,3} > \eta_{\min,4} > \eta_{\min,5}$. In this paper, the $\eta_{\min,j}$ $(j = 1, 2, 3, 4, 5)$ values are set as 0.98, 0.95, 0.70, 0.50 and 0.50 for j = 1, 2, 3, 4 and 5, respectively.

(3) Water balance equation of reservoir:

$$V_k^t = V_k^{t-1} + I_k^t - S_k^t - O_k^t - L_k^t \tag{5}$$

where V_k^t and V_k^{t-1} are the volume in the kth reservoir at the tth and $(t - 1)$th month, respectively; I_k^t is the inflow to the kth reservoir at the tth month; and S_k^t is the total water taken from the reservoir to satisfy water demand. Specifically, S_k^t for the Danjiangkou reservoir in this study includes the amount of water to be transferred through several water diversion projects. O_k^t is the outflow discharge based on the operation rules. L_k^t is the water loss of the kth reservoir at the tth month.

(4) Reservoir volume constraint:

$$V_k^L \leq V_k^t \leq V_k^U \tag{6}$$

where V_k^L and V_k^U are the lower (the dead storage) and upper (storage below the flood-limited water level in the flood season, storage below the normal water level in the non-flood season) bound of the kth reservoir, respectively.

(5) Water balance constraint of operation zone:

$$Q_i^t = \sum_{n=1}^{N_i} \alpha_{n,i} Q_n^t + Y_i^t + \sum_{k=1}^{K_i} \left(\beta_{k,i} O_k^t + \gamma_{k,i} S_k^t\right) - \sum_{j=1}^{5} \left(x_{i,j}^t - R_{i,j}^t\right) \tag{7}$$

where Q_i^t is the outlet discharge of the ith zone at the tth month, Y_i^t is the local water yield (intervening flow) produced in the ith zone, $\left(\alpha_{n,i} Q_n^t\right)$ are the discharge from the nth upstream zone that has hydraulic connection with the ith zone with $\alpha_{n,i}$ being a coefficient that takes values of 0 or 1 depending on whether they are interrelated. It is similar with the coefficients $\beta_{k,i}$ and $\gamma_{k,i}$, which determine the amount of outflow discharge and supplied water from the kth reservoir among K_i reservoirs located up to the ith zone, respectively. $R_{i,j}^t$ is the return flow of the jth sector.

(6) Minimum in-stream ecological flow constraint in control sections.

Three ecological controlling sections, i.e., the Huangjiagang, Huangzhuang and Xiantao stations, were set based on the Integrated Water Resources Planning of Hanjiang River Basin, whose minimum required flows are 490 m^3/s, 500 m^3/s and 500 m^3/s, respectively, during dry season.

(7) Non-negativity constraint.

All abovementioned variables should be non-negative.

3.2.3. Optimization Algorithm

The upstream units are supposed to extract water from the river or reservoirs firstly according to the hydraulic connections of operation zones, which indicate that available water at each confluence is influenced by the upstream water users. Therefore, a mixed simulation-optimization method is used to decide the water allocation to *j*th sector in *i*th unit for each time step, e.g., $x_{i,j}^t$.

The available water of each operation zone is simulated by the joint operation of river and reservoir system through water balance calculation for upstream operation zones, reservoirs and confluences, and then the next operation zone. Although actual water extraction and diversion for each operation zone may occur at several points along the river, water is assumed to be extracted and returned at one point for simplicity. At each water extraction point, a linear programming (LP) [45] method is embedded in the simulation procedure to obtain the water allocated to each sector and deliver the return flow to downstream confluences time-step (month) by time-step. The LP is used as a decision-support tool for guiding the system to allocate available water in a rational way.

3.3. Water Supply Risk Evaluation Module

Two criteria, which describe water supply failure occurring in any water user in terms of frequency and magnitude, are adopted or slightly revised from previous indices [33,36]. They can be defined following similar conception as reliability C_i^R and vulnerability C_i^V, respectively.

$$C_i^R = 1 - \frac{\sum_{t=1}^{T}\left[\#\left(x_i^t < WD_i^t\right)\right]}{T} \times 100\% \tag{8}$$

$$C_i^V = \frac{1}{T}\sum\nolimits_{t=1}^{T}\left(\frac{WD_i^t - x_i^t}{WD_i^t}\right) \times 100\% \tag{9}$$

where $\left[\#\left(x_i^t < WD_i^t\right)\right]$ is the number of time step with shortage in any water sector in the *i*th zone. The higher the C_i^R value is, the more reliable the local water supply is. While a higher value of C_i^V indicates that water shortage is supposed to be more devastating when water supply failure occurs in this unit, and vice versa.

4. Results

4.1. Trends of Future Water Demand

On the basis of the Integrated Water Resources Planning of Hanjiang River Basin, off-stream water demand in various water sectors (i.e., urban domestic water demand WD_1, rural domestic water demand WD_2, industrial water demand WD_3, agricultural water demand WD_4) for each unit at present and in the two planning horizons (short-term and long-term periods) under different frequency conditions along with their monthly distributions are estimated. In-stream ecological water demand WD_5 of each zone is calculated by the Tennant method [44] based on the local water resources.

The annual water demand of four off-stream water users (WD_1, WD_2, WD_3, and WD_4) for the whole study area summed up over all units are listed in Table 3. It can be seen from Table 3 that the annual total water requirement in the MLHRB will be gradually increasing with the extension of planning period, from 10,744–12,841 million m^3/year at the base year to 12,532–14,185 m^3/year at the long-term planning horizon.

According to Table 3, both the urban domestic water demand (WD_1) and industrial water demand (WD_3) are projected to significantly increase in the planning horizons resulted from living condition improvement, population growth and dramatically socio-economic development. On the contrary, the agricultural water demand (WD_4) is reduced slowly, partially because of promotion of water saving consciousness and improvement of water usage efficiency in most units. Conversely, the rural domestic water demand (WD_2) shows no significant inclination as a combined result of rising living standard but decreasing rural population due to expanding urbanization. With the increase of domestic and productive water requirement, the water supply security and sustainable development of the MLHRB will be faced with tremendous threat.

Table 3. Future annual off-stream water demand projection for the middle and lower reaches of Hanjiang River basin at present and two planning periods.

Planning Period	WD_1 (million m^3)	WD_2 (million m^3)	WD_3 (million m^3)	WD_4 (million m^3)				*Off-Stream* (million m^3)			
				50%	75%	90%	95%	50%	75%	90%	95%
Present	341	216	4514	5673	6467	7207	7770	10,744	11,538	12,278	12,841
Short-Term	424	230	5087	5582	6209	6957	7456	11,323	11,950	12,698	13,197
Long-Term	641	236	6566	5089	5636	6255	6743	12,532	13,078	13,698	14,185

4.2. Optimum Allocation of Water Resources

Long time series dataset (1956–2010) of historical hydro-climatic information, reservoir inflow, water demand and diversion scenarios are all treated as inputs to the water management module operated under the reservoir operation rules and water resources allocation rules. It should be noted that for the planning horizon, the real inflow to the Danjiangkou reservoir is obtained by subtracting the water diversion volume through the HWWDP from the natural inflow since the water source of the project (Huangjinxia and Sanhekou Reservoir) are both located in the upstream of the Danjiangkou reservoir. By optimizing the water allocated among various water sectors in different operation units based on the integrated water resources allocation model, the results of water balance between water demand and supply for the MLHRB under different frequencies in the three water demand scenarios are calculated and listed in Table 4.

It is observed from Table 4 that under the water demand scenario of the base period, the water shortage problem over the MLHRB is not serious, with an average total water deficit volume of 1029 million m^3 (6.75%) and off-stream water deficit of 605 million m^3 (5.33%), respectively. The total water supply shortage ratio for the MLHRB in the normal year (50%), moderate dry year (90%), severe dry year (90%) and extreme dry year (95%) is 6.11%, 8.90%, 11.84% and 14.95%, respectively. For the short-term planning horizon, with the synchronous increase of water demand and inter-basin water diversion capacities, the water supply satisfaction over the MLHRB will be deteriorated with total water deficit ratio of 7.67% and off-stream water deficit ratio of 6.25% for the mean annual case. It is even obvious when it comes to the extreme dry year, a 20.41% of insufficient water supply for all water sectors and 17.68% of unsatisfied off-stream water demand may present a challenge on regional water security. For the long-term planning period, the water supply scarcity in the MLHRB will be even aggravated since both water requirement and water transferred volume are further raised. The shortage ratio of mean annual total water supply and off-stream water supply would reach up to 10.01% and 8.84%. The gaps between water supply and water demand under all frequencies are considerably large, with the water supply deficit ratio of 8.49%, 12.73%, 18.76% and 26.20% for the normal year, moderate dry year, severe dry year and extreme dry year, respectively.

It can also be concluded from Table 4 that even though the urban domestic water requirement will be nearly twice in the long-term planning period as the base period, domestic water demands, both urban water demand and rural water demand, for the MLHRB are satisfied with rather high guarantee since domesticity is the most important sector and should be supplied first among all water users. Despite the gradual reduction of agricultural water demand, the water supply shortages of agricultural sectors for different typical dry year are gradually increasing, from 4.18%–11.41% in the base period to 7.06%–21.82% in the long-term planning period. The main reasons of this increase are the relatively low priority of agricultural water supply and the growth of other water users with higher priorities. Disregarding the higher priority and assurance rate of industrial water user compared to the agricultural sector, the relative industrial water supply deficit is larger than that of the agricultural counterpart, partially resulted from the operation of reservoirs located within the study area whose major function is irrigation. According to Table 4, the satisfying degree of in-stream ecological water demand is the lowest as a result of the compromise between ecology protection and relatively low tolerances of domestic and productive water deficits.

Table 4. Water balance between water supply and demand for the middle and lower reaches of Hanjiang River basin under different water demand scenarios.

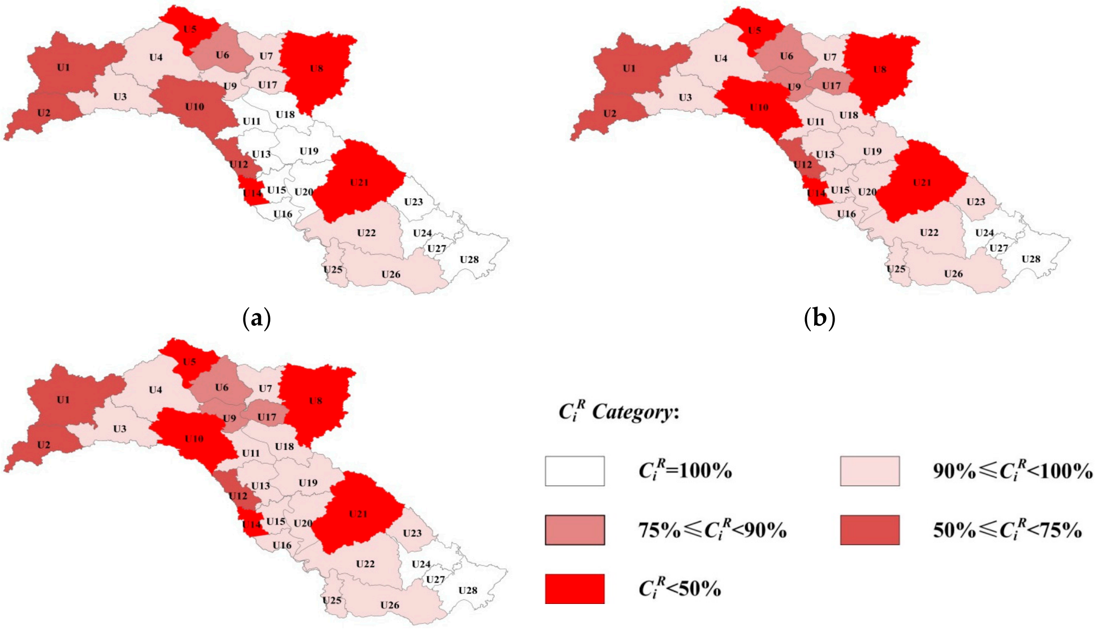
Base Period									Short-Term Planning Period									Long-Term Planning Period								
P%	**Item** [1]	WU_1	WU_2	WU_3	WU_4	WU_5	***Sum.*** [2]	***Off.*** [3]	**P%**	**Item**	WU_1	WU_2	WU_3	WU_4	WU_5	***Sum.***	***Off.***	**P%**	**Item**	WU_1	WU_2	WU_3	WU_4	WU_5	***Sum.***	***Off.***
50%	①	341	216	4514	5673	3889	14,633	10,744	50%	①	424	230	5087	5582	3889	15,211	11,323	50%	①	641	236	6566	5089	3889	16,420	12,532
	②	341	216	4241	5436	3504	13,738	10,234		②	424	230	4733	5331	3473	14,191	10,718		②	641	236	5996	4730	3424	15,027	11,603
	③	0	0	273	237	385	895	510		③	0	0	354	251	416	1020	605		③	0	0	570	359	465	1393	929
	④	0.00	0.00	6.04	4.18	9.90	6.11	4.74		④	0.00	0.00	6.95	4.49	10.69	6.71	5.34		④	0.00	0.00	8.68	7.06	11.94	8.49	7.41
75%	①	341	216	4514	6467	3889	15,427	11,538	75%	①	424	230	5087	6209	3889	15,839	11,950	75%	①	641	236	6566	5636	3889	16,967	13,078
	②	341	216	4125	6056	3316	14,054	10,738		②	424	230	4587	5784	3282	14,307	11,025		②	641	236	5687	5047	3196	14,808	11,611
	③	0	0	389	411	573	1373	800		③	0	0	500	425	607	1532	925		③	0	0	879	589	693	2159	1467
	④	0.00	0.00	8.62	6.35	14.74	8.90	6.93		④	0.00	0.03	9.83	6.85	15.60	9.67	7.74		④	0.00	0.02	13.38	10.45	17.81	12.73	11.22
90%	①	341	216	4514	7207	3889	16,167	12,278	90%	①	424	230	5087	6957	3889	16,587	12,698	90%	①	641	236	6566	6255	3889	17,586	13,698
	②	341	215	3983	6577	3136	14,253	11,117		②	424	228	4350	6276	3085	14,364	11,278		②	639	234	5225	5320	2869	14,287	11,418
	③	0	1	531	630	753	1914	1161		③	0	2	737	681	804	2223	1420		③	2	2	1341	935	1020	3299	2280
	④	0.00	0.23	11.77	8.74	19.35	11.84	9.46		④	0.06	0.91	14.48	9.78	20.66	13.40	11.18		④	0.32	1.01	20.42	14.94	26.22	18.76	16.64
95%	①	341	216	4514	7770	3889	16,730	12,841	95%	①	424	230	5087	7456	3889	17,086	13,197	95%	①	641	236	6566	6743	3889	18,074	14,185
	②	340	213	3828	6884	2964	14,229	11,265		②	422	225	3916	6301	2734	13,598	10,864		②	632	229	4647	5271	2559	13,338	10,779
	③	1	3	686	886	925	2501	1576		③	2	5	1171	1155	1155	3488	2333		③	9	7	1919	1472	1330	4736	3406
	④	0.16	1.17	15.21	11.41	23.79	14.95	12.27		④	0.43	2.14	23.02	15.49	29.69	20.41	17.68		④	1.37	3.14	29.22	21.82	34.19	26.20	24.01
Ave.	①	341	216	4514	6284	3889	15,244	11,356	*Ave.*	①	424	230	5087	6110	3889	15,740	11,851	*Ave.*	①	641	236	6566	5546	3889	16,877	12,989
	②	341	216	4202	5991	3465	14,215	10,751		②	424	230	4666	5791	3422	14,533	11,110		②	640	235	5871	5094	3348	15,188	11,841
	③	0	0	312	293	424	1029	605		③	0	0	421	319	467	1207	741		③	1	1	695	452	541	1689	1148
	④	0.01	0.08	6.91	4.66	10.90	6.75	5.33		④	0.03	0.20	8.27	5.22	12.00	7.67	6.25		④	0.11	0.25	10.58	8.15	13.91	10.01	8.84

Notes: [1] ① Water demand (WD_j): million m^3; ② Water supply (x_j): million m^3; ③ Water deficit ($WD_j - x_j$): million m^3; ④ Water deficit ratio $[(WD_j - x_j)/WD_j]$: %; [2] *Sum.* is total water balance between supply and demand; [3] *Off.* is off-stream water balance between supply and demand.

It should be noted that since the optimal water resources allocation is operated for some kind of "ideal" scenario under some arbitrary simplification, the choice of parameters of the integrated model (both ω in objective function and $\eta_{\min}$ in constraints functions) are supposed to impact the optimization results, especially for large water user sectors (WD_3, WD_4 and WD_5, see Tables 3 and 4). For example, if the $\eta_{\min}$ of all sectors are all reduced to zero, available water would be allocated completely based on the ω, the annual average total water supply deficit for the whole MLHRB will increase from 7.43% in the base year to 11.06% in the long-term planning horizon and water supply deficit in the industrial sector will become the severest case. Ignoring the adaptabilities of some water users (i.e., agricultural and ecological sectors) to adjust to extreme drought scenarios, the available water will be used to sustain healthy in-stream ecological supply after satisfying domestic water users, thus significantly reduce the water supply to industrial and agricultural activities, which are both large water consumers. It can also be inferred from the results that whether an ecological protection-oriented water supply policy is implemented may have a significant impact on the water allocation. If the net economic return of in-stream ecological water supply is reduced to the minimum among all users (equal to the agricultural sector), the average total water supply deficit for the whole MLHRB will increase from 4.41% in the base year to 7.54% in the long-term planning period. Due to the smallest values of ω and $\eta_{\min}$ parameters, water would not remain in the river channel to meet the requirement of in-stream ecological water, but to fulfill domestic and productive water demands. Trade-off between optimizing off-stream water supply and protecting in-stream ecological health needs deeper investigation. On the other hand, though the guarantee degree of urban and rural domestic water supplies are always high in terms of both large values of ω and $\eta_{\min}$, the water demand amounts of these sectors are relatively small, thus the impacts of adjusting corresponding parameters are also small.

4.3. Evaluation of Water Supply Risk

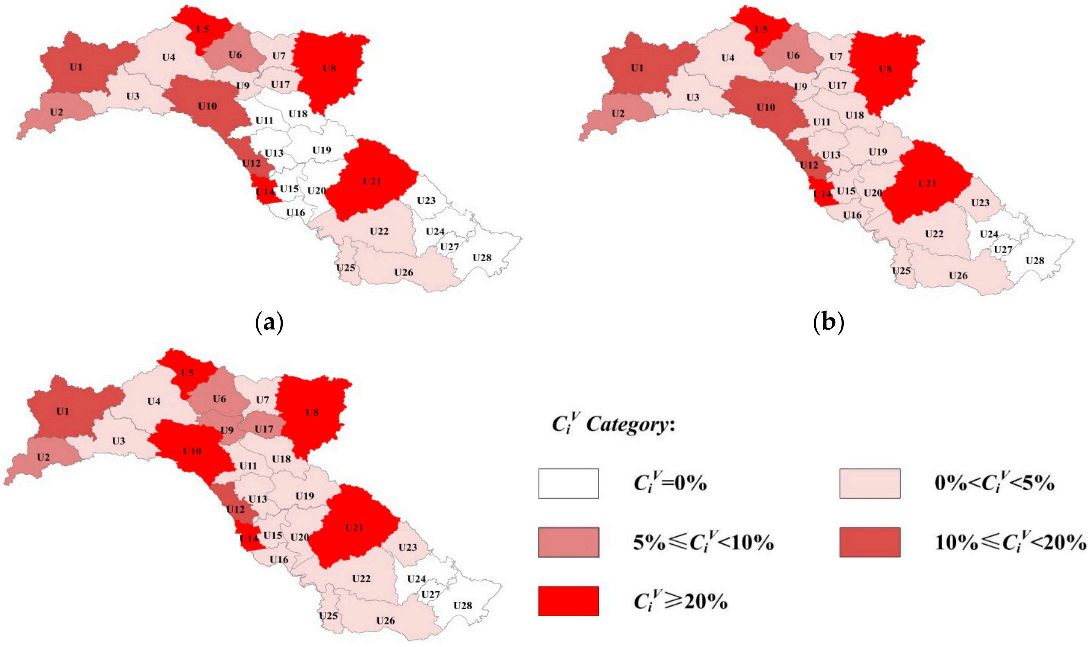
To assess the spatial distribution of water supply risk, the C_i^R and C_i^V indicators of each units in the MLHRB under different water demand scenarios are calculated and mapped in Figures 4 and 5, respectively.



(a) (b)

(c)

Figure 4. Spatial distribution of the C_i^R categories in the MLHRB basin for different scenarios: (**a**) present; (**b**) short-term planning horizon; (**c**) long-term planning horizon.



(**a**) (**b**)

(**c**)

Figure 5. Spatial distribution of the C_i^V categories in the MLHRB basin for different scenarios: (**a**) present; (**b**) short-term planning horizon; (**c**) long-term planning horizon.

For the water supply reliability C_i^R, obviously, most units along the mainstream of the Hanjiang River will almost never ($C_i^R = 100\%$) or seldom ($90\% \leq C_i^R < 100\%$) experience water supply failure under the current water demand scenario, except the two units located in northern Hubei Province, i.e., U5 and U6. The operation zones away from the mainstream may suffer from a rather unsatisfactory reliability of water supply with likely ($50\% \leq C_i^R < 75\%$) or frequent ($C_i^R < 50\%$) water supply shortage such as U8. It should be noted that U5–U8 are located within the famous humpy ground of northern Hubei in China, which is long been regarded as a drought-prone area. For the short-term planning period, water volume transferred through SNWDP will increase up to 9500 million m^3 along with 1000 million m^3 water upstream the Danjiangkou reservoir to be diverted outside the Hanjiang River basin through the HWWDP. The simultaneous increases of water demand and inter-basin water diversion are supposed to reduce the water supply reliability in the MLHRB, especially those units along the mainstream of Hanjiang River basin. For example, the frequency of water supply failure in the U17 will upgrade from seldom ($90\% \leq C_i^R < 100\%$) to sometimes ($75\% \leq C_i^R < 90\%$). This is intuitive because the water diversion projects only directly reduce the flow in the mainstream, thus impact mainly the units along the river. For the long-term planning horizon, water demand will be further increased, and the water diversion capacities of both the SNWDP and HWWDP would be extended. As a result, supply risks of many units along the mainstream of Hanjiang River are supposed to stay at the same degree under the joint effect of increasing water demand and newly operated water diversion projects. However, since part of the newly diverted water from QWDP (about 480 million m^3 of 770 million m^3) is transferred within the Hanjiang River basin to the northern Hubei, i.e., U5–U8, the ever-growing water demands in these areas will not worsen the local water supply deficits.

For C_i^V, a similar distribution pattern of water deficit level as C_i^R can be detected, indicating the synchronism of degree between the frequency (C_i^R) and the intensity (C_i^V) of water supply failure. It also sustains the rationality from sides about the classification of water supply deficit level for both indicators. For the base period, it can also be seen that operation zones that located away from the mainstream of Hanjiang River basin are more likely to face to water supply risk in intensity, such as U1, U8, U10, U12, U14 and U21. After evaluating the water supply vulnerability for the base scenario with historical inflows and current water diversion capacity, the proposed model was then run for each planning period but with added water transfer projections and new water demand scenario. Clearly, operation zones that collecting water from the mainstream of Hanjiang River basin are more sensitive to the direct human-induced alteration. The expanding water diversion is likely to aggravate water supply risk in intensity and threaten their water supply security. For instance, C_i^V values of most units along the central middle MLHRB are supposed to upgrade gradually from not ($C_i^V = 0\%$), to slight ($0\% < C_i^V < 5\%$) deficit, or from slight ($0\% < C_i^V < 5\%$), to moderate ($5\% \leq C_i^V < 10\%$) deficit in the planning period. Generally speaking, the variation range of C_i^V is smaller than that of C_i^R. For operation zones that have suffered a quite frequent and severe water shortage, i.e., U10, the imbalance between water requirement and supply will be deteriorating.

According to the indicators obtained from the optimal water resources allocation model, more water supply measures are necessary to increase the water supply capacity in the planning periods. Moreover, outside-basin water is expected to be transferred into MLHRB. The proposed risk assessment framework can provide a practical approach towards more robust decision-making of long-term water resources planning in similar strongly human-impacted areas.

5. Discussion and Conclusions

It is well recognized that the rapid exploitation that took place over the last decades, has tied the hydrologic and social systems more and more closely nowadays. The building-up water demand pressure is likely to aggravate the water scarcity around the world and is projected to intensify in the future [46,47].

To monitor, model and seek adaptive strategies against the potentially enhanced water supply risk in basins that are strongly impacted by human activities, this paper proposed an integrated water resources management model incorporating three modules to evaluate the spatial and temporal distribution of water supply risk for the mid-lower reach of Hanjiang River basin, which considers the increase of water demand and planning expanding water diversion projects in the future. The ever-growing water demand presents challenges to the water supply reliability of the operation units in the MLHRB. Despite the large available capacity of the Danjiangkou reservoir, the planned expansion of inter-basin water diversion capacity is likely to have an adverse impact on operation zones that take water directly from the mainstream of Hanjiang River. The framework proposed by the study for assessing the combined effect of increasing water demand and expanding water diversion on local water supply safety is beneficial for the water resources planning and management.

A better adaptive planning to proactively manage the water supply risk in the future usually requires long prediction of the variability of water supplies, which is always carried out by stochastic resampling or simulation of historical records. Unfortunately, historically observed data in most watersheds are no longer adequate to support robust decision-making of long-term water resources planning and management due to nonstationarity in water supply and demand [2]. Besides, persistent climate change will further enlarge this uncertainty, thus puzzling future water resources planning. All of these challenges have necessitated the development of integrated water resources management models that fully take into consideration the hydrological modeling and climate change assessment.

However, due to the limitation of existing hydrological and atmospheric models, the accuracies of simulated hydrologic regimes and projected future climate scenarios are usually accompanied with large uncertainties, which might mislead the water management decision. The ensemble of available hydrological models, General Circulation Models (GCMs) and downscaling methods within a probabilistic (e.g., Bayesian) framework seems to be a plausible approach to provide more synthetic information and reduce uncertainty, which is going to be carried out in our further studies.

Acknowledgments: This paper is financially supported by the National Natural Science Foundation of China (Grant No. 51539009 and 51579183) and the National Key Research and Development Plan of China (2016YFC0402206). The authors are also very grateful to the Bureau of Hydrology, Changjiang (Yangtze) River Water Resources Commission and National Meteorological Database of China for providing valuable hydrological and climatic data.

Author Contributions: This research presented here was carried out in collaboration between all authors. Xingjun Hong and Shenglian Guo had the original idea and wrote the paper. Le Wang helped finish the water demand prediction. Guang Yang, Dedi Liu, Haijin Guo and Jun Wang analyzed and discussed the results. All authors discussed the structure of the manuscript.

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

References

1. Wagener, T.; Sivapalan, M.; Troch, P.A.; McGlynn, B.L.; Harman, C.J.; Gupta, H.V.; Kumar, P.; Rao, P.S.C.; Basu, N.B.; Wilson, J.S. The future of hydrology: An evolving science for a changing world. *Water Resour. Res.* **2010**, *46*, W05301. [CrossRef]
2. Cosgrove, W.J.; Loucks, D.P. Water management: Current and future challenges and research directions. *Water Resour. Res.* **2015**, *51*, 4823–4839. [CrossRef]
3. Kerachian, R.; Karamouz, M. A stochastic conflict resolution model for water quality management in reservoir-river systems. *Adv. Water Resour.* **2007**, *30*, 866–882. [CrossRef]
4. Eliasson, J. The rising pressure of global water shortages. *Nature* **2015**, *517*, 6. [CrossRef] [PubMed]
5. Stocker, T.F. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014.
6. Hirabayashi, Y.; Kanae, S.; Emori, S.; Oki, T.; Kimoto, M. Global projections of changing risks of floods and droughts in a changing climate. *Hydrol. Sci. J.* **2008**, *53*, 754–772. [CrossRef]
7. Feyen, L.; Dankers, R. Impact of global warming on streamflow drought in Europe. *J. Geophys. Res. Atmos.* **2009**, *114*, D17116. [CrossRef]
8. Mishra, A.K.; Singh, V.P. Drought modeling-A review. *J. Hydrol.* **2011**, *403*, 157–175. [CrossRef]
9. Milly, P.C.D.; Wetherald, R.T.; Dunne, K.A.; Delworth, T.L. Increasing risk of great floods in a changing climate. *Nature* **2002**, *415*, 514–517. [CrossRef] [PubMed]
10. Sheffield, J.; Wood, E.F. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. *Clim. Dyn.* **2008**, *31*, 79–105. [CrossRef]
11. Olmstead, S.M.; Stavins, R.N. Comparing price and nonprice approaches to urban water conservation. *Water Resour. Res.* **2009**, *45*, W04301. [CrossRef]
12. Survis, F.D.; Root, T.L. Evaluating the effectiveness of water restrictions: A case study from Southeast Florida. *J. Environ. Manag.* **2012**, *112*, 377–383. [CrossRef] [PubMed]
13. Araujo, L.S.; Ramos, H.; Coelho, S.T. Pressure control for leakage minimisation in water distribution systems management. *Water Resour. Manag.* **2006**, *20*, 133–149. [CrossRef]
14. U.S. Environmental Protection Agency. *Control and Mitigation of Drinking Water Losses in Distribution Systems*; U.S. Environmental Protection Agency: Washington, DC, USA, 2010.
15. Guo, S.; Zhang, H.; Chen, H.; Peng, D.; Liu, P.; Pang, B. A reservoir flood forecasting and control system for China. *Hydrol. Sci. J.* **2004**, *49*, 959–972. [CrossRef]
16. Andreu, J.; Capilla, J.; Sanchís, E. Aquatool, a generalized decision support system for water-resources planning and management. *J. Hydrol.* **1996**, *177*, 269–291. [CrossRef]
17. Perera, B.J.C.; James, B.; Kularathna, M.D.U. Computer software tool REALM for sustainable water allocation and management. *J. Environ. Manag.* **2005**, *77*, 291–300. [CrossRef] [PubMed]
18. 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]
19. Jha, M.K.; Gupta, A.D. Application of Mike Basin for water management strategies in a watershed. *Water Int.* **2003**, *28*, 27–35. [CrossRef]
20. Reca, J.; Roldán, J.; Alcaide, M.; López, R.; Camacho, E. Optimisation model for water allocation in deficit irrigation systems: I. Description of the model. *Agric. Water Manag.* **2001**, *48*, 103–116. [CrossRef]
21. Shangguan, Z.; Shao, M.; Horton, R.; Lei, T.; Qin, L.; Ma, J. A model for regional optimal allocation of irrigation water resources under deficit irrigation and its applications. *Agric. Water Manag.* **2002**, *52*, 139–154. [CrossRef]

22. Liu, D.; Chen, X.; Lou, Z. A model for the optimal allocation of water resources in a saltwater intrusion area: a case study in Pearl River Delta in China. *Water Resour. Manag.* **2010**, *24*, 63–81. [CrossRef]
23. Hu, Z.; Wei, C.; Yao, L.; Li, C.; Zeng, Z. Integrating equality and stability to resolve water allocation issues with a multiobjective bilevel programming model. *J. Water Resour. Plan. Manag.* **2016**, *142*, 04016013. [CrossRef]
24. Chen, L.; McPhee, J.; Yeh, W.W.G. A diversified multiobjective GA for optimizing reservoir rule curves. *Adv. Water Resour.* **2007**, *30*, 1082–1093. [CrossRef]
25. Chang, L.C.; Chang, F.J. Multi-objective evolutionary algorithm for operating parallel reservoir system. *J. Hydrol.* **2009**, *377*, 12–20. [CrossRef]
26. Liu, D.; Guo, S.; Chen, X.; Shao, Q.; Ran, Q.; Song, X.; Wang, Z. A macro-evolutionary multi-objective immune algorithm with application to optimal allocation of water resources in Dongjiang River basins, South China. *Stoch. Environ. Res. Risk Assess.* **2012**, *26*, 491–507. [CrossRef]
27. Zhou, Y.; Guo, S. Incorporating ecological requirement into multipurpose reservoir operating rule curves for adaptation to climate change. *J. Hydrol.* **2013**, *498*, 153–164. [CrossRef]
28. Yang, G.; Guo, S.; Li, L.; Hong, X.; Wang, L. Multi-Objective operating rules for Danjiangkou reservoir under climate change. *Water Resour. Manag.* **2016**, *30*, 1183–1202. [CrossRef]
29. Zhou, Y.; Guo, S.; Xu, C-Y.; Liu, D.; Chen, L.; Ye, Y. Integrated optimal allocation model for complex adaptive system of water resources management (I): Methodologies. *J. Hydrol.* **2015**, *531*, 964–976. [CrossRef]
30. Zhou, Y.; Guo, S.; Xu, C.-Y.; Liu, D.; Chen, L.; Wang, D. Integrated optimal allocation model for complex adaptive system of water resources management (II): Case study. *J. Hydrol.* **2015**, *531*, 977–991. [CrossRef]
31. Hashimoto, T.; Stedinger, J.R.; Loucks, D.P. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resour. Res.* **1982**, *18*, 14–20. [CrossRef]
32. Mehran, A.; Mazdiyasni, O.; AghaKouchak, A. A hybrid framework for assessing socioeconomic drought: Linking climate variability, local resilience, and demand. *J. Geophys. Res. Atmos.* **2015**, *120*, 7520–7533. [CrossRef]
33. Cañón, J.; González, J.; Valdés, J. Reservoir operation and water allocation to mitigate drought effects in crops: A multilevel optimization using the drought frequency index. *J. Water Resour. Plan. Manag.* **2009**, *135*, 458–465. [CrossRef]
34. Liu, S.; Yan, D.; Wang, J.; Weng, B.; Wang, G.; Yang, M. Drought mitigation ability index and application based on balance between water supply and demand. *Water* **2015**, *7*, 1792–1807. [CrossRef]
35. Rajagopalan, B.; Nowak, K.; Prairie, J.; Hoerling, M.; Harding, B.; Barsugli, J.; Ray, A.; Udall, B. Water supply risk on the Colorado River: Can management mitigate? *Water Resour. Res.* **2009**, *45*, W08201. [CrossRef]
36. Milano, M.; Ruelland, D.; Dezetter, A.; Fabre, J.; Ardoin-Bardin, S.; Servat, E. Modeling the current and future capacity of water resources to meet water demands in the Ebro basin. *J. Hydrol.* **2013**, *500*, 114–126. [CrossRef]
37. Grimm, N.B.; Faeth, S.H.; Golubiewski, N.E.; Redman, C.L.; Wu, J.; Bai, X.; Briggs, J.M. Global change and the ecology of cities. *Science* **2008**, *319*, 756–760. [CrossRef] [PubMed]
38. Chen, H.; Guo, S.; Xu, C.Y.; Singh, V.P. Historical temporal trends of hydro-climatic variables and runoff response to climate variability and their relevance in water resource management in the Hanjiang basin. *J. Hydrol.* **2007**, *344*, 171–184. [CrossRef]
39. Chen, H.; Guo, J.; Guo, S.; Xu, C.Y.; Xiong, W. Downscaling GCMs using the Smooth Support Vector Machine method to predict daily precipitation in the Hanjiang Basin. *Adv. Atmos. Sci.* **2010**, *27*, 274–284. [CrossRef]
40. Gu, W.; Shao, D.; Jiang, Y. Risk evaluation of water shortage in source area of middle route project for South-to-North Water Transfer in China. *Water Resour. Manag.* **2012**, *26*, 3479–3493. [CrossRef]
41. Guo, S.; Guo, J.; Zhang, J.; Chen, H. VIC distributed hydrological model to predict climate change impact in the Hanjiang Basin. *Sci. China Ser. E Technol. Sci.* **2009**, *52*, 3234–3239. [CrossRef]
42. Hubei Provincial Department of Water Resources. *Dispatching Schedules of Hubei Provincial Large Reservoirs*; Hubei Provincial Department of Water Resources: Wuhan, China, 2014. (In Chinese).
43. Brekke, L.; Larsen, M.D.; Ausburn, M.; Takaichi, L. Suburban water demand modeling using stepwise regression. *J. Am. Water Works Assoc.* **2002**, *94*, 65–95.
44. Tennant, D.L. Instream flow regimens for fish, wildlife, recreation and related environmental resources. *Fisheries* **1976**, *1*, 6–10. [CrossRef]

45. Randall, D.; Cleland, L.; Kuehne, C.S.; Link, G.W.B.; Sheer, D.P. Water supply planning simulation model using mixed-integer linear programming "engine". *J. Water Resour. Plan. Manag.* **1997**, *123*, 116–124. [CrossRef]
46. Wada, Y.; Van Beek, L.P.; Wanders, N.; Bierkens, M.F. Human water consumption intensifies hydrological drought worldwide. *Environ. Res. Lett.* **2013**, *8*, 034036. [CrossRef]
47. Zhang, Q.; Han, L.; Jia, J.; Song, L.; Wang, J. Management of drought risk under global warming. *Theor. Appl. Climatol.* **2016**, *125*, 187–196. [CrossRef]