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Multi-objective Linear Programming for Optimal Water Allocation Based on Satisfaction and Economic Criterion

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Abstract In this study, a simple deterministic water allocation model was developed to optimally allocate limited available water resources among different water-use sectors. The model considers two single-objective functions and one multi-objective function. The first single objective (B_0W_1) optimizes the satisfaction levels among various water demand sectors, whereas the second single objective (B_1W_0) maximizes net economic benefits. The multi-objective (B_1W_1) combines the first two single objectives. For the multi-objective function, the model considers two optimization techniques, a simultaneous compromise constraint technique and a weighting technique to optimize both the satisfaction level and economic benefits. The model is applied to the Hingol River basin in the Baluchistan Province of Pakistan. To evaluate the model's applicability under different situations, different schemes are applied to consider variations in the minimum satisfaction level and to assign priorities to various water-use sectors. The results indicate that the value of economic benefits obtained by B_1W_1 lies between B_0W_1 and B_1W_0. This is a compromise between the two individual objectives. The model is easy to adopt under different conditions, because of its simplicity and flexibility.

Keywords Water allocation model · Optimal allocation · Satisfaction level · Economic benefits · Linear programming · Hingol River

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1 Introduction

Water is a basic necessity in a country's socioeconomic development, impacting almost all of a country's economic variables. The increasing pressures of population and industrialization, along with improved living standards, urbanization, and industrial growth, leads to competition and conflicts among various water demand sectors. Beneficiaries of a water supply can be grouped broadly into three sectors: irrigation, hydropower, and domestic. Other sectors also benefitting from water availability include industrial, navigational, recreational activities, fishing, and environmental interests. The result is a constant pressure on the limited water resources available for different uses, leading to a significant need to optimize water allocation strategies worldwide.

Pakistan once had water surpluses, fed by the enormous water resources of the Indus river basin. However, the country is now suffering from severe water resource depletion, due to changing rainfall patterns as a result of climate change and poor water management techniques [1]. Per capita water availability has dropped to 1000 m^3 in Pakistan, a threshold globally recognized as dangerously low [2]. This situation has led to chronic water stress conditions across the country. Meanwhile, the gap between water requirements and water allocation has led to conflicts between different water-use sectors.

When there is more water available than needed, water-use sectors can coexist without conflicts with few water allocation problems. In most countries, however, this is not the case; as demand increases, conflicts between different water users intensify and become more frequent. To address these concerns, Roozbahani et al. [3] discussed the application of three optimization models with single and multi-objective functions to develop new water allocation strategies to resolve water conflicts among different sectors. In further stud-

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ies, researchers explored conflicts and mitigation strategies among different stakeholders that could generate efficient, sustainable, and equitable water allocation practices [4–6].

For example, in another study, an optimization model based on economic criteria was developed to consider water allocation between agriculture and hydropower sectors in northeastern Spain [7]. Another efficient, equitable, and environmentally sustainable hydroeconomic model to analyze water usage and optimize allocation through alternative policies and strategies was developed and applied to the Mekong River basin in China and Dong-Nai basin in Vietnam [8,9]. Babel et al. [10] developed an integrated water allocation model to support optimal water allocations by reservoir operators and managers for a hypothetical reservoir. Economic management concepts and hydrologic system performance indicators, combined with engineering decision making, increase the relevance of models for water management policies and decision making [11]. Khummonkol et al. [12] proposed an integrated model for optimizing water allocation and management to maximize net economic benefits, using multi-objective optimization and rainfall forecasts. A combined optimization model of linear and nonlinear programming for short-term (10-day) reservoir operation has also been developed for the Indus River system in Pakistan for irrigation water supplies, hydropower generation, and flood protection [13].

Tilmant et al. [14] developed an integrated, stochastic, hydroeconomic model to optimize water allocation in a way that would maximize net economic returns for the Zambezi River basin in southeast Africa. Keramatzadeh et al. [15] discussed optimal water allocation to the agriculture sector based on linear and multi-goal linear programming to maximize the net economic returns (NER) to farmers in Iran's north Khorasan Province. Divakar et al. [16] developed a multi-objective economic model that would efficiently allocate limited water resources to different water sectors and applied the model to the Chao Phraya River basin in Thailand. Zhang and Song [17] developed an optimization model by combining input–output and linear programming methods to optimally allocate water resources in Hubei Province, China. Wang et al. [18] developed an optimal linear programming model based on water resources security for water allocation optimization in northern China. Roozbahani et al. [19] applied linear programming methods to assess optimal water allocation among competing sectors based on economic criteria in northern Iran. Dutta et al. [20] used the e-Water Source modeling tool to assist water managers and river operators in implementing sustainable operational water resource management.

In developing countries, including Pakistan, reservoir operators are not well trained to adopt and implement advanced, complex, and stochastic techniques for reservoir operation. Simonovic [21] discussed reservoir operation limitations and remedial steps needed to facilitate understanding and implementation by reservoir operators. Many researchers [22–25] have acknowledged that the necessarily abstract nature of complicated reservoir operation optimization models resulted in their limited application and use. Reservoir operators and managers may feel uncomfortable applying complicated optimization techniques; the stochastic nature of hydrologic variables made them even more complex [26]. Most past studies in the literature focus either on maximizing water allocation satisfaction level or net economic returns. No studies to date have considered the combined objective of optimizing satisfaction level and meeting economic criteria for a real case study reservoir operation.

This study formulated a multi-objective, linear, deterministic model for optimal water allocation. Different schemes are developed to evaluate the model's applicability under different conditions. This study applies an optimum water allocation model [10] by applying it to the Hingol reservoir in the Baluchistan Province of Pakistan, with the combined objective of optimizing satisfaction level and net economic benefits.

2 Study Area

Hingol River is one of the main rivers in the Baluchistan Province of Pakistan, with a drainage area of 34,965 km^2. The Nal and Mashkai Rivers are two major tributaries. The general slope of the main river and its tributaries are from north to south, as shown in Fig. 1. Nal River starts from the south of the town of Kalat and extends 68 km up to its confluence with the Mashkai River of approximately 278 km length up to the confluence point. The length of the Hingol River downstream of the confluence point is about 152 km. A diversion dam, named the Hingol dam, is proposed for construction, with an effective storage capacity of 643 Mm^3. The Hingol River's water budget has a surplus during the wet season (April–September) and water shortages during the dry season (October–March). The mean annual flow generated in the Hingol River is estimated at 663 Mm^3; more than 70 % of the flow is generated during the wet season because of the monsoon rainfalls. This indicates that during the dry season, Hingol River is in a water-deficit condition, and that its limited water resources must be managed efficiently for sustainable economic growth. The reservoir is a drought-prone area, where frequent water shortages occur. As such, it is a good site for implementing scientific reservoir operating policies.

3 Model Background

3.1 Conceptual Model

Figure 2 presents the basic working principles and components of this study's model. The model consists of two

Fig. 1 Location map of Hingol River basin

components: the reservoir operation model (ROM) and the water allocation model (WAM). A Hydrologic Engineering Centre's Hydrologic Modeling System (HEC-HMS) model, developed by [27], was used to estimate inflows at different river locations; these were then calibrated with the observed flows. After verification, a standard reservoir operation algorithm was generated using the Visual Basic (VB) computing tool. The algorithm includes reservoir physical characteristics and reservoir inflows as inputs; the output is the amount of available water (AW), which in turn, serves as input for the WAM.

Once constructed, the water allocation model releases water among different demand sectors depending on the studied objective. This study considers two single objectives and one multi-objective. The first single objective (B_0W_1) optimizes the level of satisfaction among different sectors; the second single objective (B_1W_0) allocates water to optimize the net economic benefits (NEB). The normal demand (D_{nor}) is defined as a sector's actual water requirements, which may or may not be fulfilled depending on the water availability. In contrast, the minimum demand (D_{min}) is the amount of water that must be allocated.

The model allocates water on the basis of water availability and objective optimization. If the available water is greater than the D_{nor} across all sectors considered, then all the sectors get their full share of water and optimization is not required. However, if the amount of total available water lies between D_{min} and D_{nor}, then the allocation may be equity based, priority based, or may be stressed supply. When the single objectives (B_0W_1 and B_1W_0) are considered, the allocation is based on linear programming; in the case of the multi-objective function (B_1W_1), SICCON and weighting techniques are used for optimization.

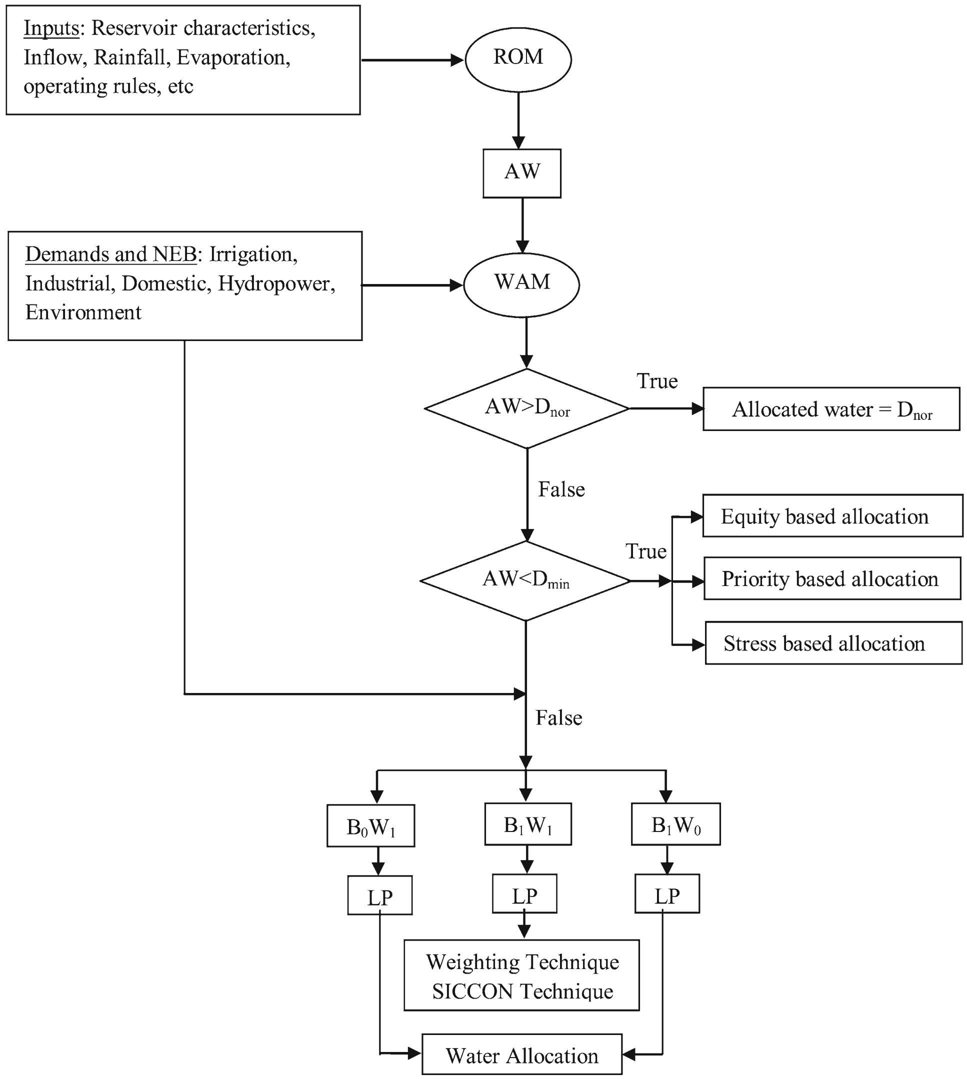
3.2 Optimization Techniques

The basic algorithm for optimally allocating limited water resources to different sectors is based on deterministic linear programming. Two optimization techniques such as weighting technique (WT) and simultaneous compromise constraint (SICCON) techniques are used to convert two single objectives into a multi-objective function.

3.2.1 Weighting Technique (WT)

In this technique, different weights are assigned to the objective functions, based on importance. The individual objectives are grouped into a single-objective function. Hence, the multi-objective decision-making problem virtually turns into

Fig. 2 Conceptual framework and components of water allocation model (*source*, adapted from Babel et al. [10])



a single decision-making problem, expressed in the following equation:

$$Z = G \times \left[\sum_{i=1}^{n} w_i \times z_i \right] \tag{1}$$

In this equation, Z represents optimal allocation values, G is the minimization or maximization function, n denotes the number of objectives, and z represents the individual objective function.

3.2.2 *Simultaneous Compromise Constraint (SICCON) Technique*

The SICCON technique is based on compromise constraint [28] approach. A compromise constraint is added to a problem to find an optimal solution between two objectives. The compromise constraint forces the objectives to be equally weighted from the individual optimal solutions. A single-objective problem with the weighted sum of the original objective functions, subjective to the compromise constraint plus the original ones, is thus solved. The compromise constraints are incorporated for each combination of objectives (by two) with two additional deviational variables. These variables represent positive and negative deviations from the ideal or supposed to-be-zero values, each of which forms the compromise constraint in the standard form:

Maximize:

$$Z = \sum_{l=1}^{k} w_l \times f_l(x) - \sum_{h \neq l} \left(\sigma_{hl}^{-} + \sigma_{hl}^{+} \right) \tag{2}$$

Subject to:

$$w_l \times \left\{ f_l(x) - z_l^{*} \right\} - w_h \times \left\{ f_h(x) - z_h^{*} \right\} + \left(\sigma_{hl}^{-} - \sigma_{hl}^{+} \right) = 0 \tag{3}$$

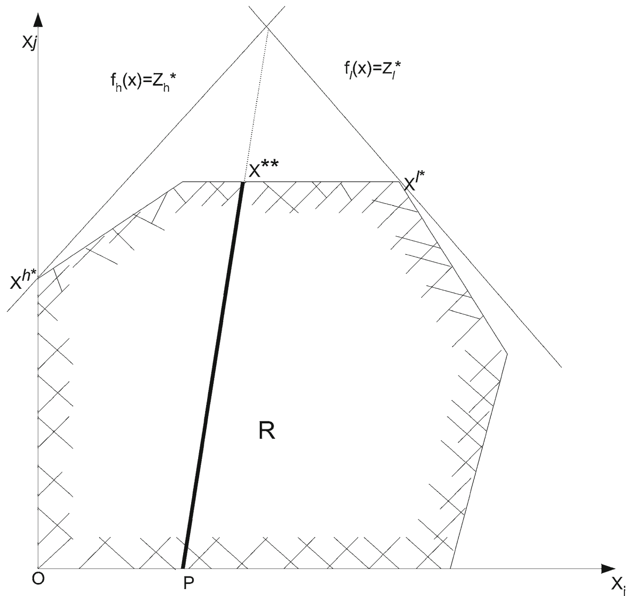


Fig. 3 Graphical illustration of compromise constraint approach

The variables σ_{hl}^{-}, σ_{hl}^{+} represent negative and positive deviations, respectively, from the supposed to-be-zero value (ideal solution) of the compromise constraint between individual objectives of z_h and z_l. The variable σ_{hl}^{-} is nonzero when the left-hand side of constraint is negative; σ_{hl}^{+} is nonzero when the value is positive. An ideal solution is achieved when both σ_{hl}^{-} and σ_{hl}^{+} are zero. Therefore, the deviational variables $(\sigma_{hl}^{-} + \sigma_{hl}^{+})$ need to be minimized, leading to the mutual exclusiveness of σ_{hl}^{-} and σ_{hl}^{+}. Figure 3 demonstrates the basic principle of the compromise constraint approach for two objective functions.

As Fig. 3 shows, the intersection of the two objective functions $f_h(x)$ and $f_l(x)$ does not fall within the feasible region (R); as such, the two objectives have to move inside R until reaching a point with a common region. In other words, the solution to the compromised constrained lies on the plane or line X^{**} in Fig. 3.

3.3 Objective Functions

The water allocation model incorporates two single objectives (B_0W_1 and B_1W_0) and one multi-objective function (B_1W_1). These objectives are briefly discussed here.

3.3.1 Optimizing Satisfaction Level (B_0W_1)

A sector's satisfaction level is the ratio of the amount of water supplied, to the sector's normal demand. Therefore, B_0W_1 optimizes total satisfaction as follows:

$$B_0W_1 = \frac{1}{n}\sum_{i=1}^{n}\frac{S_i}{D_{\text{nori}}} \tag{4}$$

In this equation, B_0W_1 is the first objective (maximization of satisfaction level); n is the number of water demand sectors; S_i is the water supplied to the sector i (m^3); and $D_{\text{nor}\ i}$ is the normal demand of the sector i (m^3).

3.3.2 Optimizing Net Economic Benefits ($\boldsymbol{B_1W_0}$)

Optimizing net economic benefits/returns (NEB) is defined as the ratio of the total economic benefits (as represented by the summation of the product of water supplied and NEB of each demand sector) to the maximum attainable total economic value. The value is defined as:

$$B_1W_0 = \frac{\sum_{i=1}^{n} S_i \times \text{NEB}_i}{\text{AW} \times \text{NEB}_{\max}} \tag{5}$$

In this equation, B_1W_0 is the second objective (maximization of net economic benefits); NEB_i represents the net economic benefits from per unit volume of water supplied from sector i (U.S. \$/m^3); AW is the total water availability (m^3); $\text{NEB}_{\max}$ is the maximum NEB among the demand sectors (U.S. \$/m^3).

3.3.3 Optimizing Satisfaction Level and Net Economic Benefits (B_1W_1)

This objective function represents the combined optimization of the single objectives, defined for the SICCON technique as the sum of two single objectives (B_0W_1 and B_1W_0) multiplied by the respective weights assigned to them, minus the sum of the deviational variables. This multi-objective function is:

$$\begin{aligned} B_1W_1 = w_1 \times &\left[\frac{1}{n}\sum_{i=1}^{n}\frac{S_i}{D_{ni}}\right] \\ &+ w_2 \times \left[\frac{\sum_{i=1}^{n} S_i \times \text{NER}_i}{\text{AW} \times \text{NER}_{\max}}\right] \\ &- \left[\sigma_{12}^{-} + \sigma_{12}^{+}\right] \end{aligned} \tag{6}$$

In this equation, B_1W_1 is the objective function representing maximization of both satisfaction and *NEB*; w_1 and w_2 are the weights assigned to first and second objectives, respectively (0–1); and σ_{12}^{+} and σ_{12}^{-} represent the positive and negative deviations from the supposed to-be-zero value between the single objectives of B_0W_1 and B_1W_0. Equation (6) without deviational variables represents B_1W_1 with the weighting technique.

3.3.4 Constrained Conditions

Equations (7)–(9) present water availability, and demand and supply constraints. These constraints are same to solve for all three objectives. A compromise constraint is introduced between $B_0 W_1$ and $B_1 W_0$ to solve the multi-objective $(B_1 W_1)$ using the SICCON technique presented in Eq. (10).

$$\sum_{i=1}^{n} S_i \leq \text{AW} \tag{7}$$

$$D_{\text{nori}} \geq S_i \geq D_{mi} \tag{8}$$

$$\sum_{i=0}^{n} S_i \leq \sum_{i=1}^{n} D_{\text{nori}} \tag{9}$$

Provided that: $S_i \geq 0$, $D_{\text{nori}} \geq 0$, $D_{mi} \geq 0$

$$w_1 \times \left[\frac{1}{n} \sum_{i=1}^{n} \frac{S_i}{D_{\text{nori}}} - B_0 W_1 \right] - w_2 \times \left[\frac{\sum_{i=1}^{n} S_i \times \text{NEB}_i}{\text{AW} \times \text{NEB}_{\max}} - B_1 W_0 \right] + \left(\sigma_{12}^{-} - \sigma_{12}^{+} \right) = 0 \tag{10}$$

However, when solving the multi-objective function $(B_1 W_1)$ with the weighting technique, this compromise constraint is not required.

4 Net Economic Benefits to Different Sectors

The detailed calculations of net economic benefits (NEB) to different water-use sectors are provided in Water and Power Development Authority (WAPDA) [29] and are briefly discussed below.

The net economic benefits for the agricultural water supply are calculated by subtracting the total production cost from the total benefits of crop production and then dividing by the total crop water requirements. To obtain monthly economic returns, this value is multiplied by the ratio of monthly water use to the total seasonal water supplied; costs such as fertilizer, labor, machinery, and other expenses are considered constant throughout the month.

The domestic water-use sector is defined as water supplied to the residences, public spaces, and offices from the reservoir to different municipalities. This sector's benefits are calculated as the difference between the water selling price and the installation and maintenance cost of the water conveyance system. This, when divided by the water volume supplied from the reservoir, results in NEB per unit volume of water use.

The net benefits from the industrial sector are computed in the same way as the domestic sector. The ratio of the difference between the water selling price and water conveyance system cost, to the water volume supplied from the reservoir, gives NEB per unit water used. Other empirical studies [30,31] can also be used to calculate NEB for water use in industrial and domestic sectors.

The hydropower sector's NEB is computed as the ratio of the hydropower generation, multiplied by the difference between the power selling price and the generation cost, to the water volume passing through the power plant.

There is no well-established method available to calculate the exact value of net economic benefits to the environmental sector. Water for this sector is used mainly to control saltwater intrusion. As such, sector benefits are calculated as the cost avoidance of not having to pay replacement costs of destroyed infrastructure due to saltwater intrusion.

5 Model Application

The next step of this study was applying the model to Pakistan's Hingol River and its five water-use sectors. The input data for the ROM include the monthly inflows into the reservoir, reservoir physical and operational characteristics (area–elevation–storage relationship), rainfall and evaporation, percolation, channel characteristics, and the monthly water demand of the different water sectors. The HEC-HMS model simulations ranged from January 1, 1980 to December 31, 2010, to estimate the inflows at different river locations and the reservoir. Figure 4 shows the reservoir and the Hingol River network, and the calibration of observed and simulated flows at various locations. Simulated and observed flows at junction J-10 (Hingol reservoir dam site) are comparable; model performance was also satisfactory at junction J-1 and junction J-6.

The model calculated inflows, after incorporating reservoir losses and gains in the reservoir operation model (ROM), are considered to be the available water (AW). This AW value is then used as the input to the water allocation model (WAM). As stated earlier, the AW in the dry season (October through March) is less than the total water required to satisfy the demand of various water-use sectors. Different sector water demands are pooled sector-wise and then considered for water allocation. To assess model applicability, the monthly available water of 24, 20, 13, 12, 16, and 18 Mm^3 in the dry season (October through March) is allocated against a monthly normal demand of 34, 25, 18, 15, 21, and 25 $\text{Mm}^{3,}$ respectively. This is one way of optimizing each sector's satisfaction level, while also optimizing economic benefits. The hydropower sector in this study is set as a non-competing sector, as water released from the reservoir passes through the power plant to generate hydropower.

The water allocation model is applied to allocate limited water resources on a monthly basis during the dry season, when the flows are relatively low and cannot satisfy the sec-

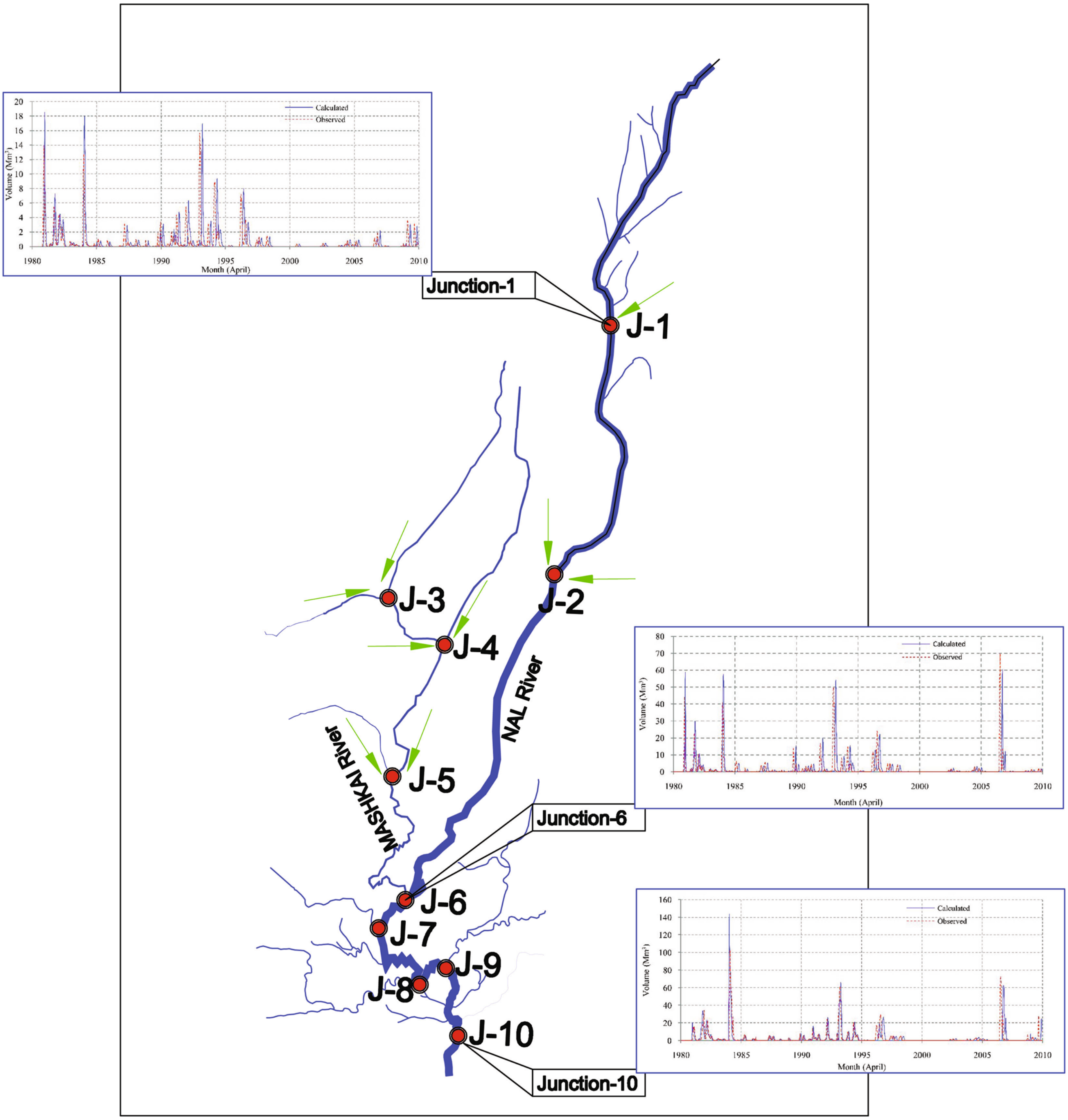


Fig. 4 Observed and HEC-HMS model simulated inflows at different locations of the river

tors' normal demand (D_{nor}). As discussed in Sect. 5.1, water is first allocated with no specific minimum demand for any sector, i.e., D_{min} is taken as zero percent of the D_{nor}. At the same time, different schemes (discussed in Sect. 5.2) allow for variations in D_{min}, allowing the assignment of priorities to different water-use sectors. This supports an analysis of model applicability and highlights the importance of decision making for improved water management. These analyses are carried out with the objectives of optimizing satisfaction level ($B_0 W_1$), optimizing net economic benefits ($B_1 W_0$), and collectively optimizing both satisfaction and economic benefits ($B_1 W_1$). Equal weights ($w_1 = 0.5 = w_2$) were assigned to the multi-objective in $B_1 W_1$, and the SICCON technique was used for optimization. Weights can be varied depending on whether satisfaction or economic returns are the priority. In many developing countries, achieving max-

Table 1 Water allocation model results for B_0W_1

Sector	Oct	Nov	Dec	Jan	Feb	Mar	Total
Agriculture							
NEB (US$/$10^3$m^3)	353	353	353	353	353	353	353
Demand (10^6m^3)	29	20	13	10	16	19	107
WAM (10^6m^3)	19	15	8	7	11	13	73
Satisfaction (%)	65	74	65	66	68	66	68
Benefit (US$ × 10^6)	7	5	3	2	4	5	26
Industry							
NEB (US$/$10^3$m^3)	128	128	128	128	128	128	128
Demand (10^6 m^3)	2	1.9	2	2	1.8	2	12
WAM (10^6 m^3)	2	1.9	2	2	1.8	2	12
Satisfaction (%)	100	100	100	100	100	100	100
Benefit (US$ × 10^6)	0	0	0	0	0	0	1.5
Hydropower							
NEB (US$/$10^3$m^3)	5	5	5	5	5	5	5
Demand (10^4m^3)	22	18	11	10	14	16	90
WAM (10^6 m^3)	22	18	11	10	14	16	90
Satisfaction (%)	100	100	100	100	100	100	72
Benefit (US$ × 10^6)	0	0	0	0	0	0	0.4
Domestic							
NEB (US$/$10^3$ m^3)	12,454	12,454	12,454	12,454	12,454	12,454	12,454
Demand (10^6 m^3)	1	1.1	0.8	0.7	0.8	1.1	5
WAM (10^6 m^3)	1	1.1	0.8	0.7	0.8	1.1	5
Satisfaction (%)	100	100	100	100	100	100	100
Benefit (US$ × 10^6)	12	14	10	9	10	14	68
Environment							
NEB (US$/$10^3$ m^3)	7	7	7	7	7	7	7
Demand (10^4 m^3)	2.3	2.3	2.3	2.3	2.3	2.3	14
WAM (10^4 m^3)	2.3	2.3	2.3	2.3	2.3	2.3	14
Satisfaction (%)	100	100	100	100	100	100	100
Benefit (US$ × 10^6)	0	0	0	0	0	0	0.1
Total benefits (US$ × 10^6)	19	19	13	12	14	18	95

imum satisfaction levels is more important than economic returns; the opposite may be true in developing countries. In this study, equal weights have been assigned for analysis.

5.1 Without Varying Minimum Demand (D_m)

5.1.1 Optimizing Satisfaction Level (B_0W_1)

Table 1 presents the monthly based water allocation to different sectors, satisfaction level, and net benefits for optimizing minimum satisfaction level (B_0W_1). In this objective, the water stress is equally distributed among different sectors.

When the objective is B_0W_1, the model first satisfies the sectors with the least D_{nor}. After that, the sectors with next higher demands are satisfied. As such, the domestic sector gets first priority followed by industry, environment, and agriculture sectors. However, the model requires that the minimum satisfaction level of all the considered sectors be satisfied. As presented in Table 1, the demands of domestic, industrial, and environmental sectors are satisfied, because the total demand of these sectors was less than the available water. The remaining water has been allocated to the agriculture sector. The domestic sector provides the highest net economic benefits followed by the agriculture, industrial, environmental, and hydropower sectors. The total value of net economic benefits with B_0W_1 is about $95-million (US) from all the water-use sectors.

Table 2 Water allocation model results for $B_1 W_0$

Sector	Oct	Nov	Dec	Jan	Feb	Mar	Total
Agriculture							
NEB (US$/$10^3$ m^3)	353	353	353	353	353	353	353
Demand (10^6 m^3)	29	20	13	10	16	19	107
WAM (10^6 m^3)	23	19	13	10	15	17	97
Satisfaction (%)	80	96	98	100	92	88	90
Benefit (US$ × 10^6)	8	7	4	4	5	6	34
Industry							
NEB (US$/$10^3$ m^3)	128	128	128	128	128	128	128
Demand (10^6 m^3)	2	1.9	2	2	1.8	2	12
WAM (10^6 m^3)	0	0	0	0.7	0	0	0.7
Satisfaction (%)	0	0	0	34	0	0	6
Benefit (US$ × 10^6)	0	0	0	0	0	0	0.1
Hydropower							
NEB (US$/$10^3$ m^3)	5	5	5	5	5	5	5
Demand (10^6 m^3)	24	20	13	11	16	18	102
WAM (10^6 m^3)	24	20	13	11	16	18	102
Satisfaction (%)	100	100	100	100	100	100	100
Benefit (US$ × 10^6)	0	0	0	0	0	0	0.5
Domestic							
NEB (US$/$10^3$ m^3)	12,454	12,454	12,454	12,454	12,454	12,454	12,454
Demand (10^6 m^3)	1	1.1	0.8	0.7	0.8	1.1	5
WAM (10^6 m^3)	1	1.1	0.8	0.7	0.8	1.1	5
Satisfaction (%)	100	100	100	100	100	100	100
Benefit (US$ × 10^6)	12	14	10	9	10	14	68
Environment							
NEB (US$/$10^3$ m^3)	7	7	7	7	7	7	7
Demand (10^6 m^3)	2.3	2.3	2.3	2.3	2.3	2.3	14
WAM (10^6 m^3)	0	0	0	0	0	0	0
Satisfaction (%)	0	0	0	0	0	0	0
Benefit (US$ × 10^6)	0	0	0	0	0	0	0
Total benefits (US$ × 10^6)	20	20	15	13	15	20	103

5.1.2 Optimizing Net Economic Benefits ($B_1 W_0$)

Table 2 shows the satisfaction levels and NEB of the water allocation model with the objective function of optimizing net economic benefits ($B_1 W_0$) against the water released to different sectors.

In this case, when the objective is optimizing NEB, the sectors having the highest NEB are satisfied first, followed by the sectors with lower benefits. Therefore, the domestic sector gets the first priority because of its highest net benefits, followed by the agriculture sector. After that, if any water is left, then the model finally releases water to industrial and environmental sectors. The domestic sector achieves the highest satisfaction level, whereas the agriculture sector gets only 90 % of its normal demand. Only a small amount of water is released to the industrial sector in January, and no water remained for the environmental sector due to its lowest benefits. Total net economic benefits in this case are $103-million (US), higher than the previous case.

5.1.3 Optimizing Satisfaction Level and Net Economic Benefits ($B_1 W_1$)

When the objective is $B_1 W_1$, optimizing both satisfaction and NEB, the SICCON technique is used and equal weights (w_1 = 0.5 = w_2) are assigned. Table 3 shows the results of water allocation, the satisfaction level achieved, and the economic benefits.

In this case, in practical, the combined objective function turns into a single objective ($B_1 W_1$), forcing the single objectives to be equally weighted from their individual optimal solutions. This is because the SICCON technique estab-

Table 3 Water allocation model results for $B_1 W_1$

Sector	Oct	Nov	Dec	Jan	Feb	Mar	Total
Agriculture							
NEB (US$/$10^3$ m^3)	353	353	353	353	353	353	353
Demand (10^4 m3)	29	20	13	10	16	19	107
WAM (10^4 m^3)	20	15	9	8	12	14	76
Satisfaction (%)	68	77	71	72	71	70	71
Benefit (US$ $\times$ 10^6)	7	5	3	3	4	5	27
Industry							
NEB (US$/$10^3$ m^3)	128	128	128	128	128	128	128
Demand (10^4 m^3)	2.0	1.9	2.0	2.0	1.8	2.0	12
WAM (10^4 m^3)	2.0	1.9	2.0	2.0	1.8	2.0	12
Satisfaction (%)	100	100	100	100	100	100	100
Benefit (US$ $\times$ 10^6)	0	0	0	0	0	0	1.5
Hydropower							
NEB (US$/$10^3$ m^3)	5	5	5	5	5	5	5
Demand (10^4 m^3)	22	18	12	10	14	17	93
WAM (10^4 m^3)	22	18	12	10	14	17	93
Satisfaction (%)	100	100	100	100	100	100	100
Benefit (US$ $\times$ 10^6)	0	0	0	0	0	0	0.4
Domestic							
NEB (US$/$10^3$ m^3)	12,454	12,454	12,454	12,454	12,454	12,454	12,454
Demand (10^4 m^3)	1.0	1.1	0.8	0.7	0.8	1.1	5
WAM (10^4 m^3)	1.0	1.1	0.8	0.7	0.8	1.1	5
Satisfaction (%)	100	100	100	100	100	100	100
Benefit (US$ $\times$ 10^6)	12	14	10	9	10	14	68
Environment							
NEB (US$/$10^3$ m^3)	7	7	7	7	7	7	7
Demand (10^4 m^3)	2.3	2.3	2.3	2.3	2.3	2.3	14
WAM (10^4 m^3)	1.5	1.7	1.6	1.6	1.6	1.6	10
Satisfaction (%)	68	77	71	72	71	70	71
Benefit (US$ $\times$ 10^6)	0	0	0	0	0	0	0.1
Total benefits (US$ $\times$ 10^6)	19	19	14	12	14	19	97

lishes a compromise between $B_0 W_1$ and $B_1 W_0$. First, the model allocates water to sectors with low D_{nor} and high NEB. Therefore, the domestic sector gets the highest priority because of its lowest D_{nor} and highest NEB, followed by the industrial sector. The remaining water is distributed between agriculture and environmental sectors, because the SICCON technique establishes a compromise between these two sectors. With this technique, every sector gets a fair amount of water, and the stress is equally distributed among different sectors while optimizing NEB. Economic benefits total $97-million (US), which is between the values obtained from the individual objective functions. These findings were consistent with results from Babel et al. [10], Khummongkol et al. [12], and Divakar et al. [32]. These researchers found that the total economic returns with the combined multi-objective function lie between the individual single objectives.

5.2 Variation in Minimum Demand (D_m)

To evaluate the model's applicability to the Hingol River, different flexible schemes were developed by varying the minimum (D_{min}) and by assigning priorities to different sectors. These schemes can assist decision makers in developing and analyzing alternative schemes that are appropriate for different local situations and that support local water management strategies. To demonstrate the model's applicability, 24, 20, 13, 12, 16, and 18 Mm^3 were allocated to dry season months (October–March); normal monthly demand (D_{nor}) was 34, 25, 18, 15, 21, and 25 Mm^3, respectively. This was the most optimal way to satisfy demand and achieve economic benefits. Again, the SICCON technique is used to optimally allocate limited water resources. The proposed model is likely to support water management decision-making

Table 4 Comparison of water allocation with different schemes for $B_1 W_1$

		Scheme-I			Scheme-II			Scheme-III			Scheme-IV			Scheme-V			Total
		D_{nor}	WAM	Benefits	S^1	WAM	Benefits	S	WAM	Benefits	S	WAM	Benefits	S	WAM	Benefits	S
Agriculture	107	86	30	80	83	29	78	79	28	74	77	27	71	97	34	91	149
Industry	12	12	1	100	12	1	100	12	1	100	10	1	90	1	0	6	6
Hydropower	124	103	0	83	100	0	81	96	0	77	92	0	74	103	0	83	2
Domestic	5	54	68	100	54	68	100	54	68	100	54	67	99	50	63	92	333
Environment	14	0	0	0	27	0	20	68	0	50	11	0	80	0	0	0	0
Total	262	206	100	79	203	99	78	199	98	76	195	96	75	206	97	79	490

S^1 is satisfaction level

processes in the Hingol River basin. Table 4 shows the results of different schemes; the schemes are discussed below.

5.2.1 Scheme-I

In this case, D_{min} is set as 0 % of the D_{nor} for all water demand sectors. With the objective of $B_1 W_1$, the model first allocates water to the sectors with lowest D_{nor} and the highest NEB. The domestic sector is set as the highest priority, because of its lowest demand and high net economic benefits. This sector is followed by industrial and agriculture sectors. However, in this scheme, no water is left for the environmental sector, as the minimum demand to meet this satisfaction is zero. Full satisfaction level in domestic and industrial sectors is achieved, while in the agriculture sector, 80 % of normal water demand is satisfied. Scheme-I produces a total net economic benefit of $100-million (US), as shown in Table 4.

5.2.2 Scheme-II

In this scheme, 20 % of the D_{nor} is considered to be the D_{min} for each sector. The model first allocates the specific amount of water to satisfy D_{min} for all the sectors and then allocates the remaining water according to the objective of optimizing $B_1 W_1$. As presented in Table 4, domestic and industrial sectors are fully satisfied, while in the agriculture sector, 78 % satisfaction level is achieved. The environmental sector gets its minimum share of 20 %. The total net economic benefit from all sectors in Scheme-II is $99-million (US), slightly less than Scheme-I.

5.2.3 Scheme-III

This scheme is similar to Scheme-II; however, in this scheme, 50 % of the D_{nor} is considered to be the D_{min} for each sector. The water allocation model first allocates the minimum specified amount of water to each sector; the remaining water is then allocated to the other sectors based on the $B_1 W_1$ objective. The environmental sector receives a minimum share of 50 % of its normal demand, while the agriculture sector achieves 74 % satisfaction, and domestic and industrial sectors are fully satisfied. The total value of net economic benefits in this scheme is $98-million (US), less than the value from Scheme-I and Scheme-II.

5.2.4 Scheme-IV

Based on the objective of $B_1 W_1$ *being considered*, the model may set a particular sector as having the lowest priority. In reality, however, that sector may be important for its social and/or environmental aspects. Therefore, Scheme-IV considers varying percentages of the D_{nor} as D_{min} for particular sectors. Table 4 shows the results when the D_{min} is set as 60, 80, and 70 % of the D_{nor} for industrial, environmental, and other sectors, respectively. The model first allocates the water according to minimum specified demands to all sectors; the remaining water is allocated based on the objective function of $B_1 W_1$. The total economic benefit under this scheme is $96-million (US), less than the value obtained in previous schemes. This is due to the fact that the environmental sector receives more water, but produces the least economic benefits.

5.2.5 Scheme-V

In this scheme, equal priorities are assigned to specific sectors. Agriculture and domestic sectors are set as prioritized sectors, to assist decision makers and planners in analyzing the results when sector(s) are equally important. As with previous schemes, the model first satisfies the demands of prioritized sectors; after that, any remaining water is allocated to other sectors. As Table 4 shows, agriculture and domestic sectors see a satisfaction level of 92 %; no water is left for other sectors. In this scheme, equal priority is assigned to agriculture and domestic sectors; as such, the model allocates water by establishing a compromise between the two sectors, which considers the joint objective of optimizing satisfaction level and economic benefits ($B_1 W_1$).

6 Conclusions

This study developed and applied a deterministic integrated water allocation model, incorporating two single-objective functions and one multi-objective function. The first single objective ($B_0 W_1$) optimizes the satisfaction level of different water demand sectors, whereas the second objective ($B_1 W_0$) optimizes net economic benefits (NEB). The multi-objective ($B_1 W_1$) combines the two individual objectives. The model was applied using different flexible schemes, including varying minimum demand ($D_{\min}$) and assigning sector-specific priorities to demonstrate model applicability under different conditions.

When the first objective ($B_0 W_1$) is considered, the highest priority is given to the sector with the lowest normal demand (D_{nor}), then to the sector with the next higher D_{nor} and so on. For the second objective ($B_1 W_0$), water allocation is based on net economic benefits (NEB). The multi-objective function ($B_1 W_1$) uses the SICCON technique, establishing a compromise between the two single objectives to optimize both minimum satisfaction level and NEB. The net economic benefit value using the SICCON technique lies between those obtained by two single objectives ($B_0 W_1$ and $B_1 W_0$), because it is a compromise solution.

The optimal water allocation model, using the multi-objective function ($B_1 W_1$), has many benefits; it maximizes satisfaction levels while addressing economic benefits. The model's flexibility in addressing varying sector priorities can increase the satisfaction level of particular sectors. Five flexible schemes demonstrate the model's applicability and provide a wide range of possible situations that decision makers may encounter where they must optimize satisfaction levels, or balance satisfaction levels and net economic benefits.

This study's results demonstrate techniques for optimally allocating limited water resources; the model is effective and widely adoptable because of its simplicity and flexibility under different local situations. The linear multi-objective program presented in this study can be modified to solve any optimal water allocation problem (simple to complex), in Pakistan and other countries. The next step is to further test and apply this model in practical real-world settings.

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