Evaluation and Administration of Water Resources: A Comprehensive Review

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Abstract:
Although water is a renewable resource, groundwater levels across the world are experiencing a continuous decline. The primary sectors consuming water include agriculture, domestic use, industry, and environmental needs. The rising challenges of unplanned urbanization, rapid industrialization, exponential population growth, changing agricultural practices, limited technical expertise, and inadequate implementation of suitable technologies at the river basin level have all contributed to the growing scarcity of clean and fresh water. In India, agriculture remains the largest water consumer, followed by increasing demands from industrial processes and urban areas due to expanding economic activities. Therefore, it becomes imperative for policymakers to accurately determine the optimal water demand across various sectors based on the available resources. This paper provides a critical review of existing methodologies for assessing water resources and explores management strategies to address future challenges.

Keywords: IWRM (Integrated Water Resources Management), WEAP (Water Evaluation and Planning), BHIWA (Basin-level Hydrological Information for Watershed Assessment)

1. Introduction

Globally, more than 60% of rivers have undergone fragmentation due to various hydrological modifications [1]. According to the World Business Council for Sustainable Development, water-related stress arises when annual renewable freshwater availability per capita falls below 1,700 cubic meters, while severe water scarcity—adversely affecting economic growth and public health—emerges when this figure drops below 1,000 cubic meters. The United Nations projects that by 2050, global population will increase by approximately 3.5 billion people, predominantly in developing countries. This demographic surge is expected to significantly raise water demand unless offset by improvements in water conservation and recycling efforts.

A critical issue for the future is securing sufficient freshwater for food production. Sustainable freshwater access must be aligned with responsible water management, taking into account climate change, environmental conditions, and socio-economic factors. Increasingly, global consensus emphasizes the importance of protecting ecosystems when allocating water for human consumption, ensuring that ecological and environmental integrity is preserved [2][3][4]. Thus, a thorough assessment of existing water resources is necessary for integrated planning, development, and management.

Integrated Water Resources Management (IWRM) is conceptualized as "a process that promotes the coordinated development and management of water, land, and related resources to maximize economic and social benefits equitably without jeopardizing the sustainability of essential ecosystems" [5].

An integrated hydrological model, incorporating institutional mechanisms for water allocation as well as economic and environmental factors, is essential for effective water resource management at both sub-basin and basin levels. Precipitation—both as rainfall and snowfall—plays a central role in the hydrological cycle and is a primary renewable source for surface and groundwater. A portion of this precipitation infiltrates the ground, replenishing aquifers, while the remainder contributes to surface flow and storage in reservoirs. Consequently, water becomes accessible in the form of surface runoff, groundwater, and direct rainfall.

The economic valuation of water use offers vital insights for policy decisions related to its equitable distribution among sectors, investment planning in water infrastructure, and the design of economic mechanisms such as pricing structures and water trading markets [6].

Water Resource Assessment: Concepts and Approaches

Water resource assessment involves quantifying available surface and groundwater resources in terms of quantity, quality, temporal, and spatial distribution. Key elements include:

- Hydrological Analysis: Evaluation of rainfall, runoff, infiltration, and evapotranspiration.
- Water Balance Studies: Assessment of inflows and outflows within a basin.
- Remote Sensing & GIS Applications: Used for watershed delineation, land-use classification, and change detection.
- Groundwater Estimation Techniques: Include water table fluctuation methods, geophysical techniques, and aquifer modeling.
- Water Quality Assessment: Monitoring chemical, physical, and biological parameters.

Role of Modeling Tools in Water Resources

To operationalize the principles of Integrated Water Resources Management within a coherent analytical framework, various modeling approaches have been developed. These integrate hydrological, agricultural, economic, and institutional elements and serve as effective tools for enhancing water resource management [7]. Numerous studies have investigated the application and benefits of such models.

Several simulation tools have been specifically designed to support water resource planning and policy-making at the river basin level. Prominent among these are the River Basin Simulation Model (RIBASIM) [8], MIKE Basin [9], Water Balance Model (WBalMo) [10], the Multi-sectoral Integrated Operational Decision Support System (MULINO-DSS) [11], and the Water Evaluation and Planning System (WEAP) [12]. These tools allow for comprehensive analysis and scenario planning to better address the complexities of water allocation and sustainability.

WEAP Model

The Water Evaluation and Planning (WEAP) system is a widely used tool developed to simulate current and future water demand and supply scenarios. Initially applied in the Aral Sea region [12], WEAP has gained recognition for its user-friendly interface, which facilitates the analysis of diverse water allocation scenarios. It enhances awareness and understanding of key water resource management challenges. For example, it has been effectively applied in the Steelpoort sub-basin of the Olifants River in South Africa [13].

The WEAP21 version of this model was designed to bridge the gap between water resource management and watershed hydrology, ensuring accessibility, ease of use, and relevance to a broad spectrum of stakeholders in the water sector [14]. The model generates essential outputs for each scenario, including unmet water demands across sectors, streamflow at catchment outlets, and storage volumes in reservoirs [15].

In the Tulkarem district of the Palestinian Territories, WEAP21 was used to model future water availability, assess risks and pricing, and plan for reliable and equitable allocation. The decision support system (DSS) component of WEAP21 was applied through a combination of stakeholder engagement, data collection, and simulation modeling [16].

An integrated assessment of water scarcity was conducted for three river basins in India—Mahi (Gujarat), Thamiraparani (Tamil Nadu), and Bhima (Maharashtra)—using WEAP in combination with QUAL2K and MODFLOW models. The impact of climate change was also examined, with the Thamiraparani Basin found to be most severely affected [17].

The Municipality of Nablus also utilized WEAP to address ongoing water shortages. The study involved three phases: data collection, capacity-building on WEAP applications, and modeling of different water management strategies. Findings indicated that unmet water demand is projected to increase in the coming years [18].

WEAP21 integrates both hydrological and management modeling to support IWRM (Integrated Water Resources Management). It is capable of simulating catchment hydrology at various scales and addressing both aggregated and disaggregated water demand across sectors. This makes it particularly suitable for catchments with limited to moderate data availability [19].

In the Alana Valley, multiple scenarios were developed using WEAP21, including:

- Reference scenario
- Water quality improvement scenario
- Groundwater augmentation
- Reservoir construction
- Climate change impact
- Irrigation intensification
- Downstream water requirement scenario

These simulations supported strategic planning for water resource management in the valley [20].

Similarly, WEAP was employed to estimate future water demands in the Niamey and Tillabéry regions of the Niger River Basin [21]. The model is applicable to both municipal and agricultural water systems and can address a range of concerns including:

- Sectoral water demand analysis
- Conservation strategies
- Water rights and allocation priorities
- Streamflow simulation
- Reservoir operations
- Ecosystem requirements
- Cost-benefit analysis of projects [22]

In another case, WEAP was calibrated against actual dam operation data, demonstrating its capacity to replicate historical reservoir volumes accurately. Five alternative supply scenarios were modeled for the Jordan Valley (JV), including:

- Business-as-usual
- Increased use of treated wastewater in irrigation
- Climate change effects

- Combined scenarios involving reuse and agricultural modifications

These projections were used to estimate the supply-demand gap through the year 2050
A schematic representation of the WEAP model structure is provided in

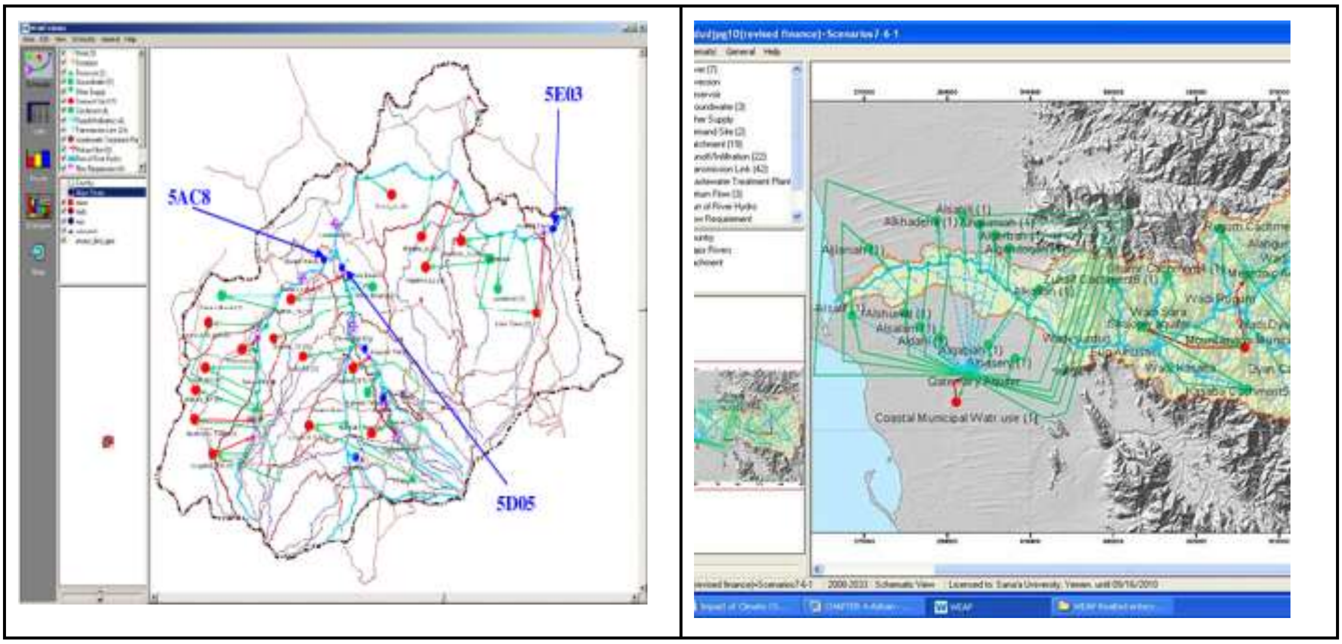

Figure 1. However, it should be noted that WEAP has certain limitations, such as its inability to simulate daily operations or perform least-cost optimization for supply-demand balancing.
In developing countries like India, the Basin-wide Holistic Integrated Water Assessment (BHIWA) model is also utilized to examine the effects of changing land and water use. This model captures the interdependencies within the terrestrial hydrological cycle and is capable of evaluating sectoral water uses and analyzing development scenarios. It has been successfully applied to the Brahmani and Sabarmati river basins [24].
In line with this integrated approach, the Water Resources Department of Odisha, under the World Bank-aided Water Resources Consolidation Project (WRCP), developed a comprehensive State Water Plan. This plan reflects IWRM principles and coordinates input from stakeholders across multiple sectors. The endorsement of the plan by the State Water Resources Board marks a significant step forward in ensuring equitable and sustainable water distribution, while maintaining ecological balance.
Effective implementation of IWRM in India requires not only technical tools like WEAP and BHIWA, but also institutional strengthening and strategic managerial reforms to support the sustainable governance of this critical natural resource.

Conclusion

In the absence of substantial improvements in water conservation and recycling practices, the global demand for water is expected to continue rising. One of the most pressing challenges in the coming decades will be securing sufficient water resources for food production.
Integrated water resource models have proven valuable in analyzing both biophysical and socioeconomic dimensions of water allocation across sectors such as agriculture, domestic use, and industry. These tools assist policymakers in understanding the dynamics of water availability and demand, as well as in anticipating possible environmental and socioeconomic consequences in specific regions.

However, a critical limitation of many existing models is their limited ability to address shortcomings in current water allocation systems. They often fall short in demonstrating how existing water supplies can be holistically integrated into broader water management frameworks at the sub-basin and basin levels. Addressing this gap is essential for achieving sustainable and equitable water resource management in the future.

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