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Review Article

Assessment of Hydrological and Water management Models for Ghba Subbasin, Ethiopia

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ABSTRACT

The aim of this study was to assess the hydrological and water resource management model in the Ghba River subbasin that could be used for resilient water allocation strategies. Water allocation is the most important sector with regard to water resources management due to its social, economic, hydrological, and environmental aspects, and many scholars and researchers have been driven to investigate the dynamic interrelationships among hydrological, environmental, and socioeconomic factors affecting water allocation.

This review is seeking to include a comprehensive survey of existing publications and scholarly papers on the use of the WEAP modeling system as an effective tool for dealing with different problems associated with planning, management, and analysis of hydrology and water resources systems. Recent trends in the integration of WEAP modeling with other modeling systems, such as artificial intelligence systems, are discussed. Some of the limitations and challenges facing the application are highlighted. This article provides a foundation of references and studies which will help scholars, researchers, and academics who are interested in using the WEAP modeling system in combination with hydrology and water resources management and planning.

Keywords: Hydrology, Water resource, WEAP modeling system, Resilient water allocation

INTRODUCTION

Background

The Ghba sub basin is one of the main sub basins of the Tekeze Atbara river basin, which is a major international river originating in Ethiopia and flowing out to the Nile basin [1]. As shown in Figure 1 the subbasin lies between altitudes of 936 at the confluence with the Tekezze River and 3314 m at Mugulat near Adigrat. The topography is mountainous with plateaus that are extremely scored by river gorges, and the river network contains entirely of single thread channels, with narrow (50 m–150 m) alluvial plains [2]. To challenge the problems of recurrent shortage of water supply and food insecurity, efforts have been made to harvest runoff water for potable water supply, irrigation, fishery and hydropower developments [3-5].

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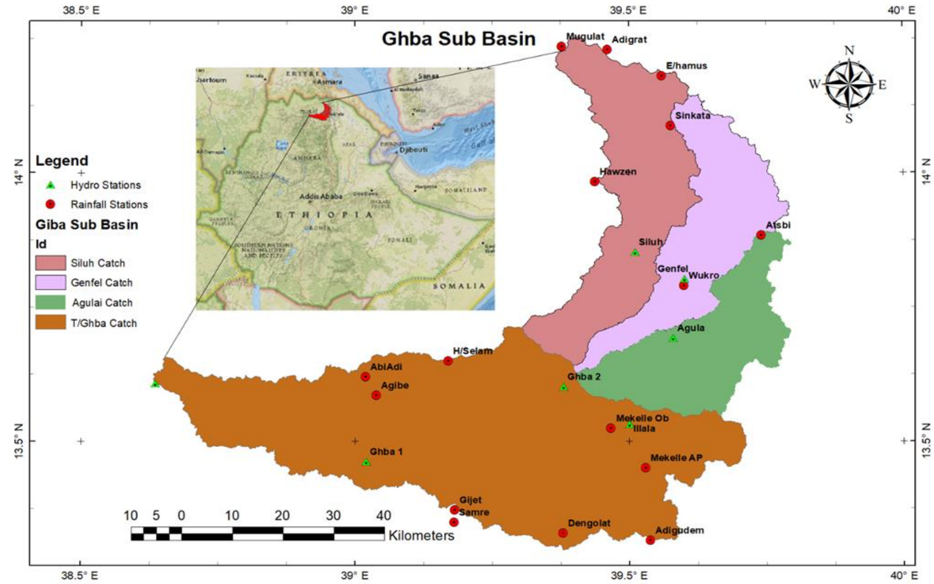

Figure 1. Location and distribution of rainfall and streamflow monitoring stations.

LITERATURE REVIEW

To assist communities in this region who have been reliant upon emergency support, in recent years the government of Ethiopia has been committed to address and satisfy the shortage of water supply in the region by building a mega project like Ghba water supply project and Gerebsegen multipurpose dam (both for irrigation and water supply) [6]. However, food security and potable water supply status varies significantly from year to year, as the subbasin experiences variations in rainfall patterns [7]. Therefore, continues research is required to better understand how food security and water supply can be strengthened. Existing studies in the sub basin tells water scarcity and inefficient utilization of the available water resources are the key factors for food deficiency and shortage of water supply [8,9].

During the past two decades, human water withdrawals in the sub basin were extremely increased due to rapid growth of population and increasing living standard [10,11]. Water resource scarcity is not only affected by hydroclimatic conditions but also due to continuous increased human water demand, socio economic development and governmental policies [12,13]. Therefore, water scarcity could be considered from both physical and economic viewpoints [14]. As studied by Gebremicael, Mohamed and, Shiferaw, Gebremedhin climate variability is a factor that can significantly change the timing, quantity and distribution of water in the region. However, economic water scarcity is the commonly and easily noticeable water scarcity in the subbasin. The economic water scarcity can be defined as a condition where renewable freshwater resources are physically available but deficient in financial/socioeconomic and institutional capability that bounds societal skill to use that water [15,16].

The uncertain water resource potential in the subbasin means that the present water withdrawal percentage is uncertain. The figure below Figure 2 shows that, as of 2018, the percentage of water withdrawal from the subbasin is estimated to be around 0.2 BCM, These withdrawals of water are estimated up to 20% of the catchment yield the. This shown that the subbasin water is underutilized. And their recent withdrawals were summarized in three main sectors: the drinking water sector, including public supply and self-supplied domestic use, the industrial sector, including mining and commercial water use, and the agricultural sector, including irrigation, and livestock water use [17,18].

The study by Rijsberman, reflects that even if water usage efficiency could be improved dramatically at some places, meeting these water demands was a big contest in many parts of the world, especially in developing countries of Asia and Africa as these regions were facing severe water scarcity in the past decades and forecasted in the coming decades [19]. Ethiopia is among the list of countries having renewable water resources below the calculated threshold of 1500 m^3/capita/year by the year 2030.

Finally, yet importantly, understanding the spatial and temporal changing patterns/variability of water scarcity and its driving factors at global scale is very important for sustainable use of water resources.

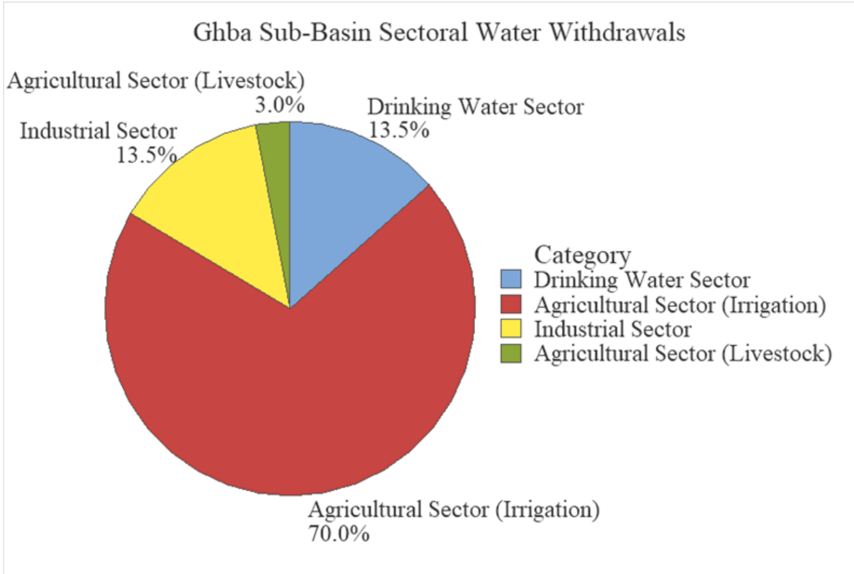

Figure 2. Sectoral water withdrawals in the Ghba sub-basin.

Hydrological and water management problems in the subbasin

Hydrological processes are basic steps to characterize modelling approach in simulating the actual physical characteristics of catchments/basin. The Ghba sub basin hydrological processes are characterize by semi-arid region hydrological process which is quite different from hydrological processes of humid environments. The study area is situated in semi-arid region hence, climate change and variabilities are common. Therefore, the availability of water resources is also known to be inconsistent at different spatio temporal scales. Many articles have been published to describe the differences between semi-arid and humid hydrological processes such as Castillo, Gomez-Plaza, de Wit, Castillo, Gomez-Plaza and, Bergkamp.

Runoff generation in semi-arid areas is mainly affected by surface conditions not by the rainfall amount and intensity. These, shows interaction among vegetation cover, micro topography and the hydrological response is possibly more important in semi-arid than in humid areas. Vegetation may increase the infiltration capacity of soils and reduce overland flows. In semi-arid catchments, there is no guard of the soil to raindrop impact which can cause a reduction of infiltration capacity due to shortage of vegetation cover. In swift, less vegetation cover in the study area may lead to the absence of organic matter in the soil which can have substantial effects on interception, infiltration, evapotranspiration, and runoff response. Additional factor that can meaningfully influence the hydrological processes of a catchment is the variability of precipitation. Precipitation in semi-arid areas tends to be more variable than in humid areas. All this climate variabilities in semi-arid region makes the water management a bit complex.

Increasing water demands for agriculture, industry and domestic uses remains to put more pressure on the economic scarce water resources in these water limited environments of Ghba subbasin. The probable regional climate change stances yet another challenge to the sustainable management of natural resources and the environment for the better living standard of the society.

Management of water resources from Ghba sub-basin viewpoint needs inclusive interdisciplinary analysis, evaluation of present and future circumstances, and formulation of multiple management plans. However, there are common scientific and technical difficulties that limit us from understanding, forecasting and eventually guiding the management of water resources. The major scientific questions are the lack of understanding of hydrological processes at the basin scale and inadequate understanding of the coupling between hydrological, ecological and climate systems.

In summary, the economic water scarcity of the Ghba subbasin has numerous governing factors to escalate the complexity of the system ranging from natural and anthropogenic climate changes to the complex socioeconomic, institutional and hydrological factors. This helps to increase the knowledge of the basin hydrology and water availability for making a sound and sustainable water regime. Therefore, this study on hydrology and water management is also required to achieve the national water policy objectives, which focuses on the need to establish an all inclusive water management system that incorporates natural elements of the total water cycle as part of principles of sustainable development.

Impact of socioeconomic change on water management processes

Current water resources management in general, are characterized by increasing complexity, uncertainties due to climate and global change and shifting socio-economic conditions offer new challenges that cannot be tackled within the established management paradigm which relies on a command and control approach. Studies show that in the coming decades extreme variability in water resources and significant decreases in stream flow will be major threats across sub Saharan African countries.

The need and demand for water in the Ghba sub basin is becoming severe with the growing population. World Bank project was designed at addressing this challenge. The evaluation of the intervention shows that there is a substantial increase in water supply in the city because of the sub project. However, the increase in water supply has not been able to meet up with the already established and increasing demand.

As reported by George, Faures the urbanization rate in Sub-Saharan Africa is increasing from time to time. Mekelle the capital city of Tigray region and other new emerging cities in the Ghba sub basin are one of these fast growing sub-mega cities in recent times. Mekelle, as the administrative seat and political capital of Tigray, the city attracts the highest number of migrants from other parts of the region. As the supply of water must be guaranteed for all, to meet the basic human needs, there is a need for advanced water supply planning and management system for the city in order to bring about ultimate changes in the ways water is currently used as well as distributed among different categories of users. The status of demand side management, in particular, is vital from perspective of the fact that the supply of water cannot be just increased open ended to meet the otherwise increasing demands from the household, commercial, construction, industry and other sectors as well as the needs of the environmental reserves.

Population growth and economic development activities as well as improvements in living standards of the population would require increasing demand for water. In case of Mekelle and other emerging new cities in the sub basin, which are growing into a large city, the construction boom including construction of buildings, hotels, residential houses, higher education and health facilities, access roads and other marketing infrastructures and services, the expansion of condominiums and real estate housing developments, the expansion of manufacturing and service sector establishments that has occurred during the last decade, and the substantial increase in its population that is expected to occur in the coming years assumes a sustainable water supply planning and management. Therefore, environmental managers, urban planners and policy makers need to find solutions for urban development impact and alternative water sources for the existing and future pressures.

Hydrological modeling

Hydrological modelling is the conceptual representation of a complex real hydrologic features *i.e.* a simplification of real world system by mathematical expressions for input variables which describe the quantitative relationship between rainfall and runoff. Some of the variables are precipitation, evaporation, soil moisture, and stream flow. The impact of socioeconomic development and hydrological variability on water management strategies and other human interactions with environments can be branded using hydrological models. They can simulate the baseline and future water resource potential in the basin or sub basin for allocation purpose. Hydrological models can also provide an outline to conceptualize and understand the impact of climate change trends and socioeconomic development on water resource potential and allocation options. This in return helps decision and policy makers in formulating/proposing strategic water allocation options.

Hydrological models representing the real world in a small computer by maintaining the laws of energy, momentum, and continuity equations. Among the specific functions includes stream flow forecasting that supports water allocation, reservoir operation, and drought studies. Therefore, quality of measurements, accessibility of data of the basin, and the hydrologic model estimates are controlling the accuracy of stream flow simulations. In addition, some of the challenges comprise, choosing the most suitable model structure for selected basin, and quantification of all sources of model uncertainty in hydrologic model simulations. This requires a detailed knowledge of the role of individual components in each hydrologic model for improved assessment of their applicability and also to know the differences between simulations of various hydrologic models. Under this sub title, as shown in Figure 3 it is very important to discuss the idea of model uncertainty according to the different sources of uncertainty with respect to model complexity. The idea is explained graphically below to show how it is possible to decrease the amount of uncertainty by taking the optimal point that compensates or makes a balance between simple and complex models to minimize the model error. This helps the modeler to decrease the uncertainty of the model he/she built (Figure 3).

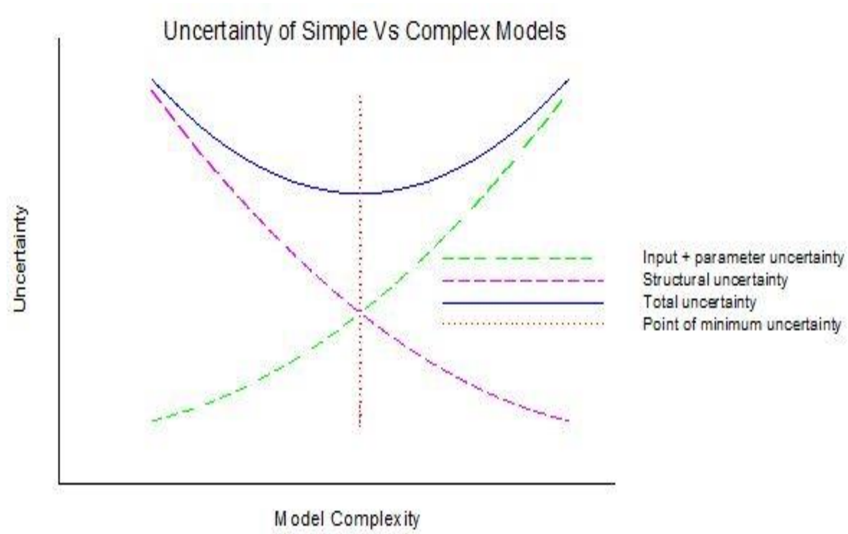

Figure 3. Dependency of various sources of uncertainty on the model complexity.
Source: Adopted from Solomatine and Shrestha

Some of the hydrological models are discussed here, Soil and Water Assessment Tool (SWAT) is a river basin scale model. It can predict and simulate the effect of land management practices on water, agriculture, and sediment in complex watersheds with different soil categories, land use, and management aspects over long time periods. Watershed is segregated into Hydrological Response Units (HRUs). AVSWAT-2000 is an arc view extension along with Graphical User Interface (GUI) of the SWAT model. SWAT-CUP is another calibration/uncertainty or sensitivity program interface for SWAT, whereas QSWAT is a QGIS interface for SWAT. SWAT-CUP, and QSWAT is available in SWAT.

Variable Infiltration Capacity (VIC) is additional physical distributed hydrological model with components such as land cover, soil, snow model, meteorology/meteorological input data, frozen soil formulation, dynamic lake/wetland model, flow routing. MIKE family modelling system has a number of models, namely, MIKE URBAN covers water distribution and storm water drainage systems. MIKE FLOOD includes a specialized 1D and 2D flood simulation engines, enabling to model any flood problem. MIKE 21 handles data assessment for coastal and offshore structures. MIKE HYDRO Basin facilitates multisector solution alternatives to water allocation and water shortage problems, climate change impact assessments on water resources availability and quality. Other related detailed information about hydrological models is available in Strapazan, Haidu, Jahandideh-Tehrani, Helfer, SANTOS, FERNANDES, and Yu, Disse.

WEAP is a water demand and supply accounting model (water balance accounting), and has an integrated water resources planning systems (water supplies, demands, and forecasting). Built-in five hydrological models for rainfall runoff and infiltration, evapotranspiration, crop requirements, and yields, surface water/groundwater interaction, and in-stream water quality. Simulation and optimization of water resources management *via* various scenarios DSS modules. Graphical interface provides a simple, powerful, means for constructing, viewing, and modifying the configuration. Model building capability with several built-in functions, user defined variables, and equations. Dynamic links to spreadsheets and other models (LEAP, MODFLOW), embedded linear program, solve allocation equations, flexible and expandable data structures, powerful reporting system graphs, tables, and maps.

These days, the development of a vigorous distributed hydrological model which needs little calibration to sidestep over parameterization and make best use of available spatial data is becoming prevalent. Thus, WEAP modeling system is becoming more important and has a potential to develop dynamic and flexible distributed hydrological models and water allocation planning, it has also a potential to simulate different impacts under what if scenarios of socioeconomics development, climate change, population growth, and LULC changes.

WEAP modelling system used in water and hydrological sectors

One of the success criteria of the WEAP modeling process is the appropriate and proper selection of software used in the development of the hydrological model and water allocation strategies. Many modeling packages have been developed to make it easier to structure and implement hydrological models in different fields, such as SWAT, HEC-HMS, Mike Shi, Mike Basin, HBV, Mike 11, and so on. Through the review of various publications and papers related to the application of WEAP model in the water sector, the most used software packages are SWAT, and HEC-HMS. In general, these packages are simple to use and provide a diversity of functions and offer calibration and validation techniques. Moreover, they boost cooperative modeling and connection with very large datasets. According to our review, the largest number of studies and research was carried out using SWAT by 71% of the total studies in the field of water, while the WEAP software was used in about 29% of all studies, and this may be due to the fact that WEAP is more suitable for water allocation strategies, optimization, and requires more experience and has a higher cost *i.e*., it's licensed compared to SWAT.

The Water Evaluation and Planning (WEAP) model was first formulated by the Stockholm Environment Institute-Boston (SEI) in 1990. This DSS is designed to help planners balance water supplies and demands, ensuring sustainable use of water. The technique can be used in municipal and agricultural systems as well as single catchment/subbasin/basin systems, or complex trans boundary river basin systems. WEAP simulates the impact of a range of natural and engineered factors on water resources in these systems, including rainfall runoff, base flow and groundwater recharge from precipitation, sectorial demand analyses, water conservation, water allocation priorities, reservoir operations, hydropower generation, pollution tracking and water quality, vulnerability assessments and ecosystem requirements. It is a comprehensive water resources planning tool that can help development teams create water balances, scenario analyses, and plans. The water resources simulation model is designed to address issues such as allocation of limited water resources, environmental quality, and policies for sustainable water use. This book provides an integrated approach to water resources development that considers the demands of consumers, water quality, and environmental preservation.

The WEAP model can simulate how water is allocated throughout a river basin over time based on a user-specified step. The WEAP laboratory is focused on studying different water development and management strategies. WEAP evaluates a variety of water development and management options in order to create a comprehensive policy analysis. It considers the effects of sectoral demand, water conservation, water rights, and allocation priorities, groundwater and stream flow simulations, reservoir operations, hydropower generation, pollution tracking, ecosystem requirements, and vulnerability assessments. Finally, it evaluates the benefits and costs of each option, in order to determine the most effective course of action.

WEAP is flexible enough to handle any data that is relevant to describing a water resources system. This means the system can characterize its water supplies and demands in daily, weekly, monthly, or annual time steps. The simplicity of the tool makes it applicable at a wide range of spatial and temporal scales. Indeed, WEAP has been used to analyze a wide variety of optimal water allocation strategies based on priorities set for each demand site. WEAP is unique among water allocation tools because it considers the full range of human needs, including drinking, sanitation, agriculture, and energy production.

A WEAP application typically includes several steps. The study describes the time frame, spatial boundary, system components, and configuration of the problem. The water supply data provides a snapshot of how much water is being used, how much pollution is being discharged, how much water is available, and how much water is available to be used. There are multiple future scenarios based on different policies, costs, technological development, and other factors that affect demand, pollution, supply, and hydrology. Scenarios are created by imagining different outcomes based on different assumptions. The scenarios are evaluated regarding water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables. Since the WEAP modeling system was first developed in 1990, it has been used in many research projects focused in numerous areas throughout the world.

The WEAP model is being used in a variety of parts of Africa to improve water resource management plans for economic and ecological sustainability. In Zimbabwe and Volta, it was used to plan and evaluate multi purpose reservoirs for the improvement of smallholder/marginalized livelihoods and food security. In Ethiopia, the model was used to evaluate present and future water resource development for efficient use of water allocation scenarios.

Challenges and limitations of WEAP model

It is evident from the above that many researchers and modelers performed extensive studies on water issues and water systems and achieved substantial outcomes and progress using WEAP model. Even though there is much research and experience, there are still some difficulties, constraints, and challenges that limit the comprehensive use of the WEAP modeling approach in issues related to and specialized in water resources systems. Luck of knowledge and experience challenges in utilizing the WEAP modeling system properly with water resource management and hydrology model structure applications.

To create an effective water management system, a lot of knowledge and experience are required to understand how different systems interact. The WEAP modeling system is handy and simple when describing causality relations among many variables and factors. However, the convenience and ease of using these models may lead to incorrect results due to simplified models that are focused on extraneous and irrelevant details. To prevent these types of problems, you need knowledge and experience to check for causes and evaluate the relationships between them. These tests and checks help to verify the existence of causal relationships within an integrated modeling process, which increases the reliability of the model. The WEAP modelling system's hydrology model structure is well-represented through both simulation of the watershed's hydrology and irrigation of pastureland, while the allocation algorithm is used to supply demand from a combination of surface and groundwater supplies. The supply is commonly determined by users' preferences and the priority is given to meet in-stream flow demands first. Irrigation requirements are always seconded by altering the amount of irrigated land in a watershed, the model is capable of investigating the subsequent impacts of irrigation, which have well documented influences on both in-stream and riparian ecosystem service and function. Often, without a strong understanding of the tradeoffs, these impacts are observed. The WEAP model has been found to be useful in understanding the ecosystem services provided throughout a watershed and the tradeoffs of different management systems. Therefore, expertise knowledge is mandatory in using the WEAP modeling system for performing hydrology and water resource system models.

Model Validation is extremely relevant in issues relating to water resources that are addressed by mathematical modeling and, in particular, by the approach of WEAP modeling. Unfortunately, according to Schluter, Savitsky, the validation of a WEAP model is also requires expertise knowledge in understanding of all input data in the context of reality. The reason verifying the internal model frame is so complicated is that it is based on theoretical and technical principles. Weaver, Lempert concluded that it is theoretically problematic because it is directly connected and closely linked to the unique theoretical problems of testing the validity of the scientific argument. Moreover, the complexity of the issue stems from the lack of any recognized validations for models that might be used to approximate the problem frame.

DISCUSSION

Effective water management includes integrating a number of hydrological, environmental, social, economic, administrative, and political factors into the decision-making process for exploiting, managing, and maintaining available water supplies, power, and agricultural sectors. This study provides a comprehensive review of research on the use of WEAP modeling system for water management. We examined the various applications of WEAP modeling in hydrological and water systems, and found that it may be a useful tool for water supply, power, and agricultural water management.

CONCLUSION

Reviewing issues and problems surrounding water quality management, water footprints, water conservation policies, regional water resources, environmental water management, drainage water quantity, wastewater reuse, salinity reduction, modeling surface water and groundwater, urban water resources, water scarcity assessment, flood risk, trans boundary systems, and sustainable management of municipal water was conducted. We discussed the various aspects of the WEAP method, including its various forms, measures, advantages, and drawbacks. The WEAP modeling system can provide a complete understanding of how different subsystems in a hydrological or water system interact. This software is powerful and helpful when it comes to managing emerging complicated issues and relationships, as well as modeling and analyzing hydrological systems. The WEAP modeling system can integrate numerical and descriptive techniques, systematically investigate and evaluate complex systems, and generate different internal relations for water resources systems. However, the WEAP modeling system has some limitations that need to be addressed. Before beginning to model a water management system, it is important to have a solid understanding of the system's basic parameters and factors that affect it. WEAP has some difficulties when working with complex structures and systems that change in different social and environmental conditions. Nevertheless, a number of studies and investigations suggested that the WEAP modeling methodology be combined with other modeling techniques to resolve these issues and increase performance. Several studies used the WEAP modeling system in combination with fuzzy logic, artificial neural networks, geographic information system, agent based modeling and simulation, Bayesian network, analytic hierarchy method, and impact analysis. Thus, the WEAP modeling system has been improved by combining it with these methods, which have made it more accurate and versatile. As a result, the impact of WEAP modeling on water resource systems' decision making, planning, management, and research has been positive. Our analysis has shown that the WEAP modeling system can be used successfully in a variety of applications related to water and agriculture water management economics, power, policies, and strategies. This will help to resolve many of the main problems with water resource management, such as groundwater management in agriculture, crop water relations, rainwater harvesting, saline agriculture, farm level water management, and global climate change.

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