https://doi.org/10.48048/tis.2022.3050

Water Demand and Supply Analysis using WEAP Model for Veda River Basin Madhya Pradesh (Nimar Region), India

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Received: 2 November 2020, Revised: 1 May 2021, Accepted: 12 May 2021

Abstract

Significant gaps exist in water management strategies implemented in the sub-basin of Narmada River, the Veda River Basin. Hence, the main goal of this study is to predict water demand and supply, recharge and draft with the use of the Water Evaluation and Planning System (WEAP) Model. The study area is watershed of the Veda River located in the Nimar region of Madhya Pradesh, and Middle Narmada River sub-basin of India. In this study, the WEAP model is used as a decision support system for watershed management. The WEAP model uses water balance approach for the generation of results, based on that 4 types of scenarios have been developed are high population growth, high industrial growth, rainwater harvesting, and water storage structures for future trends. The unmet water demands were simulated in all administrative blocks, catchments, and industries which amounting to 9.58×10^8 m^3 in 2011 and 9.65×10^8 m^3 in 2030. Results suggested that the addition of water storage structures as well as artificial groundwater recharge structures reduce the unmet water demand for domestic consumption and meet irrigation water requirements.

Keywords: Watershed management, Water evaluation and planning system (WEAP), Demand and supply analysis, Scenario generation, Decision support system

Introduction

Water is one of the important yet a hidden resource and not much focus is given to it in this era of modern technologies; worldwide, there is a lack of access to water for daily use. Availability of water gives life whereas its unavailability can lead to death also [1]. India is an agriculture-based country, so the importance of water is most. There are various problems of water resources that can create a big issue like water shortage causes drought, water excess due to heavy rainfall causes flood, irregular operations of reservoirs impact on power generation and irrigation water supply leads to low production of power and less yield of crop respectively [2-4]. To overcome all such problems different computer-based mathematical tools Decision Support System (DSS) has been widely used in the field of water resources [5-10]. DSSs are systems incorporating modelling, data analysis and management of the database. It also helps in the process of decision-making. There are various ArcGIS generated thematic maps (Digital Elevation Model, Blockwise Map, Drainage Map, Land Use and Land Cover map etc.) used to input data in the study area. There is no prior work related to water management in the Veda River basin. Although, there are many studies related to watershed management using the WEAP model MABIA method. Amount of water required by the catchment is mostly due to crops in the catchment. DSS development for basin management is beneficial to manage future water demands [2,9,10]. WEAP has also been used for watershed management and to estimate future water demand and water allocation based on demands [2,11-13]. This study includes river basin management of Veda River (Narmada river's left-bank tributary) falls in middle Narmada sub-basin. The study area is chosen based on water shortage and a huge variation in water during monsoon and non-monsoon period. There is a sudden rise in the level of water in the river during the monsoon period (July to October). Since the river width is small and the water level is high that results in inundation of the area nearby river whereas, water in non-monsoon period shows the shortage for irrigation as well as sometimes for drinking purpose also [14]. The water available in the watershed is used to fulfil various demands like domestic, irrigation, industrial, and ecological demand. The WEAP model has been used in the basin to manage agricultural and domestic water systems to govern various issues such as water allocation priorities, conservation of water, streamflow and groundwater simulations, and water storage structure. The key objective of this study is to simulate water demand and supply, groundwater recharge and draft with the help of the WEAP model.

Materials and methods

Study area

In this study, Veda River basin has been taken that geographically lies within the Narmada middle sub-basin. Veda River watershed covers a total area of 4,108.02 km^2. Veda River originates from the Saykheda Village, Jhirnia block (tehsil) in the Khargone district of Madhya Pradesh. Geographically the origin coordinates of the river are 21°38′ northern latitude and an eastern longitude of 75°57′. The river flows in North-westerly direction for the entire length of 110.38 km to meet the Narmada from the left, at downstream of Mandleshwar dam. The Veda River basin majorly shares an area of Khargone district and some parts of Khandwa, Burhanpur and Barwani districts of Madhya Pradesh. The geographical extension of watershed ranges from longitudes 75°20′ E to 76 °09′ E and latitudes 21°23′ N to 22 °09′ N.

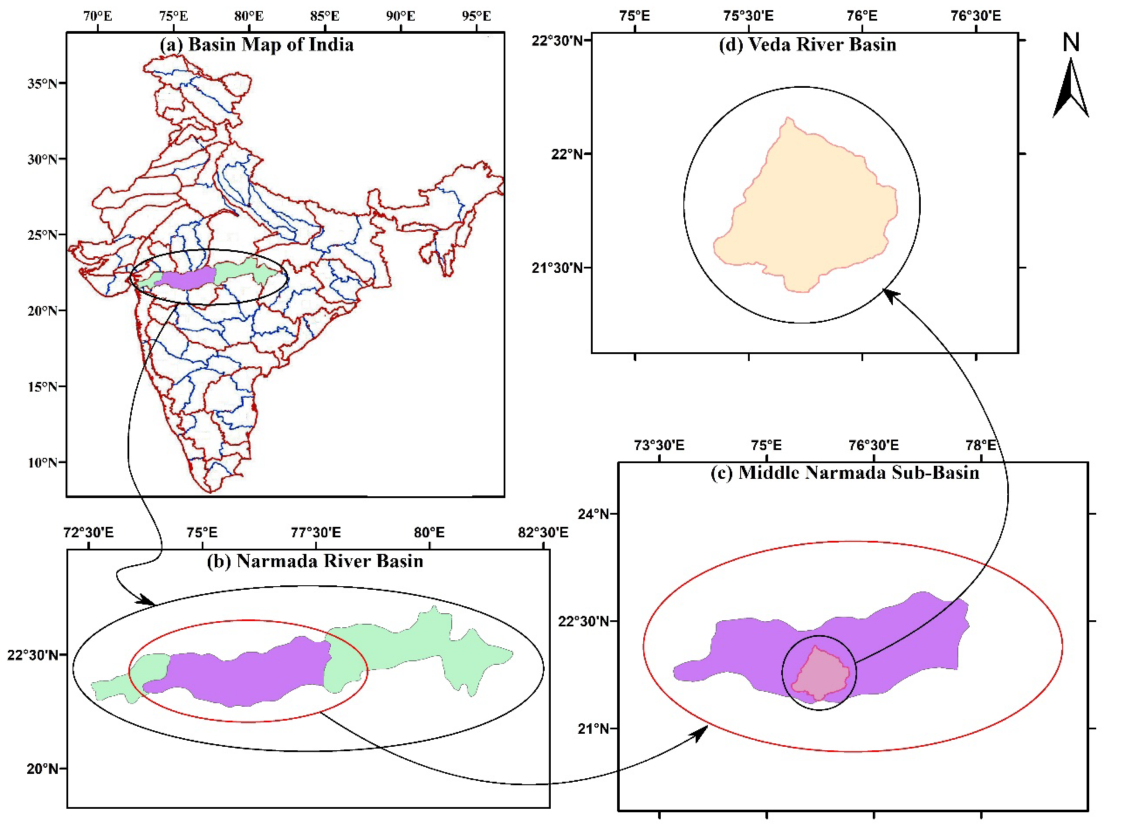

Figure 1 Location map of study area (a) Basin Map of India, (b) Narmada Basin, (c) Middle Narmada Sub-Basin, (d) Veda River basin.

The shape of the catchment area is fan type that means tributaries are near the same size. Thus, it can be said that the time of concentration of runoff is almost same due to catchment slope as well as river tributaries and hence runoff is greater at the outlet [14]. The normal rainfall in the study area is 835 mm per year and mostly convective type precipitation; nearly 92.8 % of the total rainfall is recorded during the south-west monsoon in central India (i.e., from the Arabian Sea) [15]. The study area concerning the basin map of India is shown in **Figure 1** in which map (a) shows the location of Narmada River basin, lies in central India. **Figure 1** map (b) shows the 3 sub-basins of Narmada River basin (i.e., Upper Narmada sub-basin on eastern side, Middle Narmada sub-basin on central part and Lower Narmada sub-basin on western side), map (c) in **Figure 1** represents the location of study area in the middle Narmada sub-basin, whereas map (d) shows the study area and its geographical extension. Various Maps generated through ArcGIS is shown in **Figure 2**. Land use land cover (LULC) map shows that maximum land is covered by agricultural fields (39.50 %) in the study area. Drainage Map shows a dendritic pattern of river network. There are nine blocks in the study area namely Bhagwanpura, Jhirnia, Burhanpur, Sendhwa, Khandwa, Segaon, Khargone, Bhikangaon, and Kasrawad, each of them is considered as a demand site for the administrative block as well as for the catchment as C1, C2, C3, …, C9 respectively. The soil in the study area is dominantly black cotton soil having properties such as field capacity 39.70 %, wilt point 22.90 %, saturation 44.44 % and available water capacity as 16.80 % [16] and also the cotton crop is maximum produced crop in the study area [17].

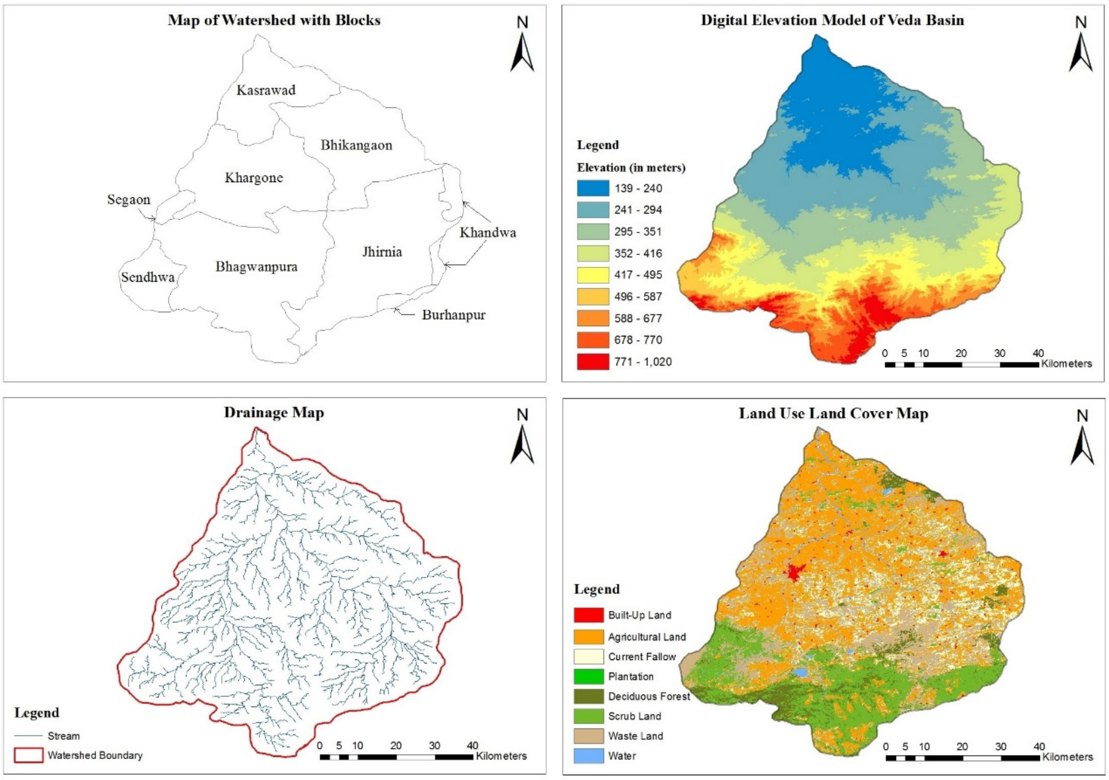

Figure 2 Various GIS-based maps: (a) Administrative Blocks, (b) Topography (Digital Elevation Model), (c) River Network (Drainage Pattern), (d) Land Use Land Cover Map.

WEAP model

The WEAP model has been developed by the Stockholm Environment Institute. It assesses a wide range of options for water development and management as a policy analysis tool, and takes into account the multiple and competing uses of water systems. It allows us to predict the results of the entire system in different scenarios, and to make comparisons between the different alternatives to evaluate a wide range of water supply and conservation choices. WEAP provides a comprehensive collection of model structures and processes that can be used to examine a broad variety of problems and challenges faced by water planning, including environmental concerns, watershed conditions, anticipated demand, habitat requirement, climate regularity, operational objectives and service [18]. Different work has been done using WEAP model in different areas like watershed management [2], irrigation in agriculture [11], canal water supply [12], water analysis of basin [13], etc. There are 5 methods available in WEAP for catchment processes (such as evapotranspiration, runoff, irrigation demands and infiltration), which include MABIA (FAO 56, dual KC, daily), rainfall-runoff (simplified coefficient method), rainfall-runoff (soil moisture method), irrigation demands only (simplified coefficient method) and plant growth (daily; CO_2, water and temperature stress effects). In this study WEAP model's MABIA (a French acronym of "MAitrise des Besoins d'Irrigation en Agriculture" which means "control of irrigation needs in agriculture" [19]) method is used for supply and demand analysis of all administrative blocks, catchments and industrial sectors. MABIA method is a daily computation of evaporation, transpiration, irrigation requirements and scheduling, crop growth, which includes modules for estimating reference evapotranspiration and the capacity of soil water. WEAP-MABIA is a full program framework for modelling crop water requirements and various water balance components. The MABIA method uses the 'dual' Kc method for estimation of evapotranspiration, where Kc is crop coefficient value is equal to the sum of 'basal' crop coefficient (Kcb) and a coefficient representing evaporation from the soil surface (Ke). MABIA approach can be used to model both crops and non- agricultural land types, like forests and grass-lands [19].

Methodology

A flow chart in **Figure 4** representing the general methodology of the study from study area selection to the generation of results. Then the collection of data is done, **Table 1** enlists various data collected and their respective sources. After collecting data, schematic view of WEAP has been prepared as shown in **Figure 3**. Then all collected data fed into WEAP model. WEAP model's MABIA method requires daily data for the simulation. The reference scenario is taken from 2012 - 2030 using current accounts year as 2011.

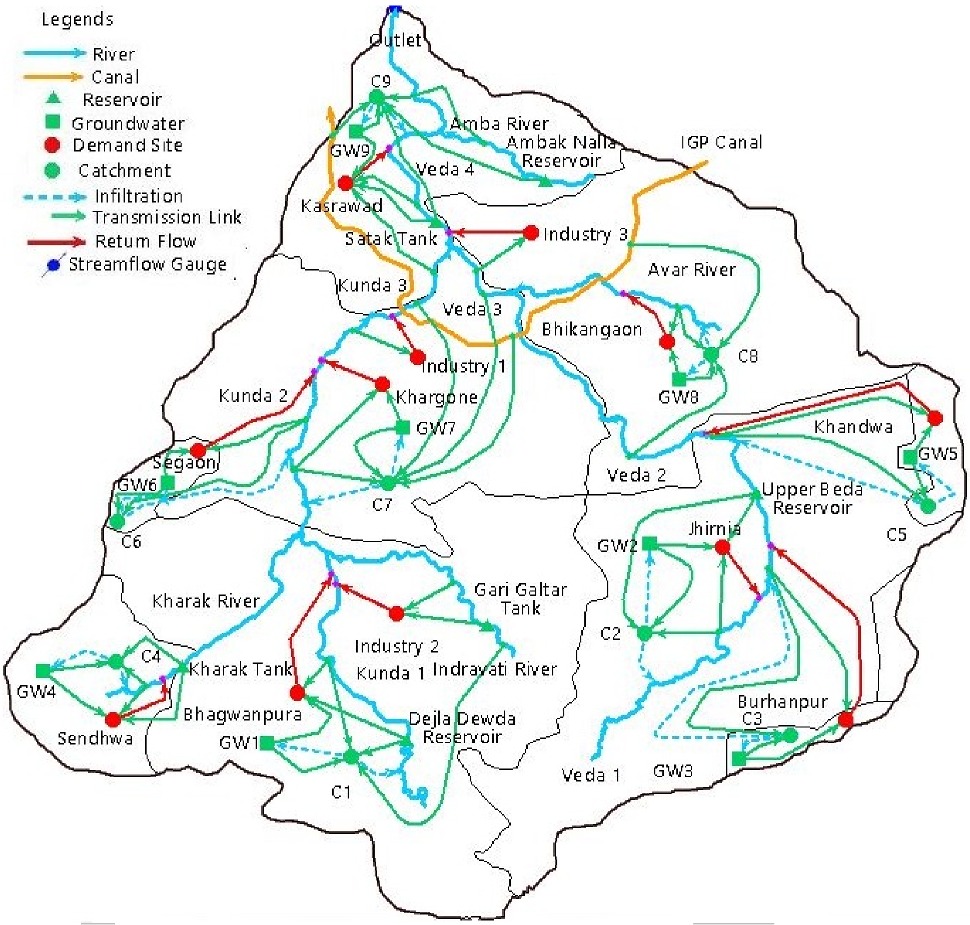

Figure 3 Schematic of the study area.

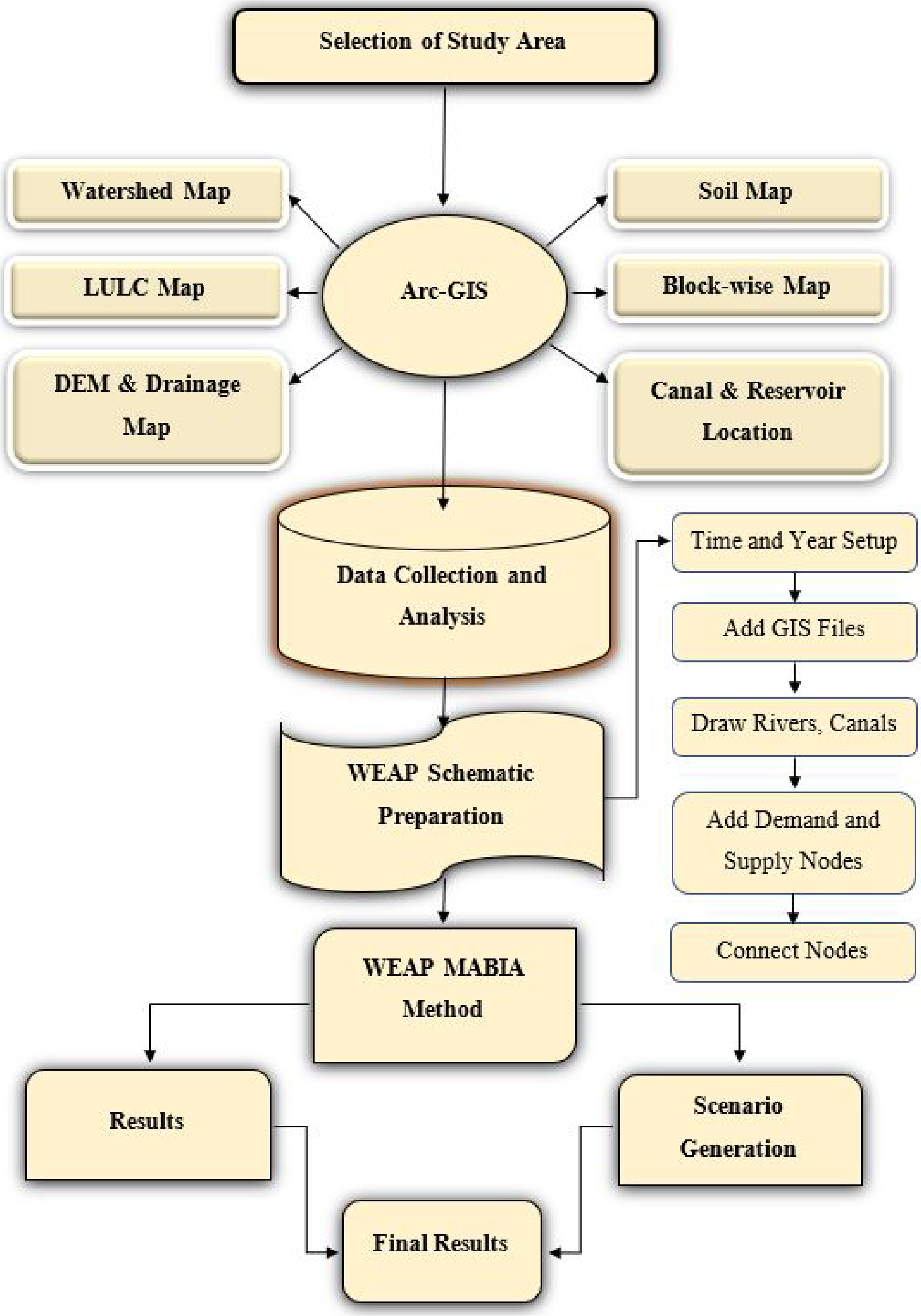

Figure 4 Flow chart of methodology.

After feeding data in the Model for each node and river, the final model is run to simulate the demand and supply of water for the Veda River watershed and managing the same in 'what if' scenarios for 19 years (2012 - 2030). Keeping in mind the physical, demographic and economic characteristics of the watershed, the following 4 scenarios were generated (high population growth, high industrial growth, rainwater harvesting, and additional storage and supply structures) and their respective results are estimated. Supply priority for domestic water supply is given as 1, for agricultural catchment is set to be 2 and last for industrial water supply from the sources like rivers, groundwater nodes and local reservoirs or canals.

Table 1 Data collected and their sources.

S. No.	Data Type	Parameters	Source
1	Population	Human Population Livestock Population • Growth Rate	Census of Madhya Pradesh [20,21] United Nations World Population Prospects [22]
2	Climate data	• Minimum and maximum temperature • Radiations • Precipitation	Global weather data [23] Data Centre, Madhya Pradesh Water Resources Department, Bhopal
4	Land use data	• LULC Map • Total land area	Bhuvan
5	Reservoir data	• Storage capacity	Madhya Pradesh Water Resources Department Website [24]
6	Groundwater Data	• Initial Storage • Groundwater withdrawal • Groundwater recharge	Central Ground Water Board Report [15,25-28]
7	Soil	• Soil Map	National Bureau of Soil Survey & Land Use Planning, Nagpur, India
8	Crop	• Crop name • Category of crop • Stage length • Kcb (Basal crop coefficient) • Ky (Yield Response factor) • Height of crop (m) • Depletion factor • Minimum & Maximum rooting depth (m) • Planting date	Agricoop.nic.in [17,29-31] WEAP Crop Library and Food & Agriculture Organization irrigation and drainage paper number 56 [32]

Results and discussions

After inserting the data and running WEAP model, the Result View of the model shows the output information both in graphs and tables. Water demand simulated for the reference year scenario having a slight variation from 2011 to 2030. **Figure 5** represents the total unmet water demand for each month for all the catchments and administrative blocks for the water year 2011 whereas, **Figure 6** shows the annual variation of unmet water demand in all demand sites from the year 2011 - 2030.

Unmet demand is nearly 0 in July, August, September, April and May for the base year 2011 and maximum for December month which is 287.08 MCM (million cubic meters). The unmet demand of all Administrative Blocks, including domestic and other demands of population and livestock. The Unmet Water Demands in all Administrative Blocks for the year 2011 - 2030 have been simulated which comes to be 26.15 MCM in 2011 and 32.20 MCM in 2030.

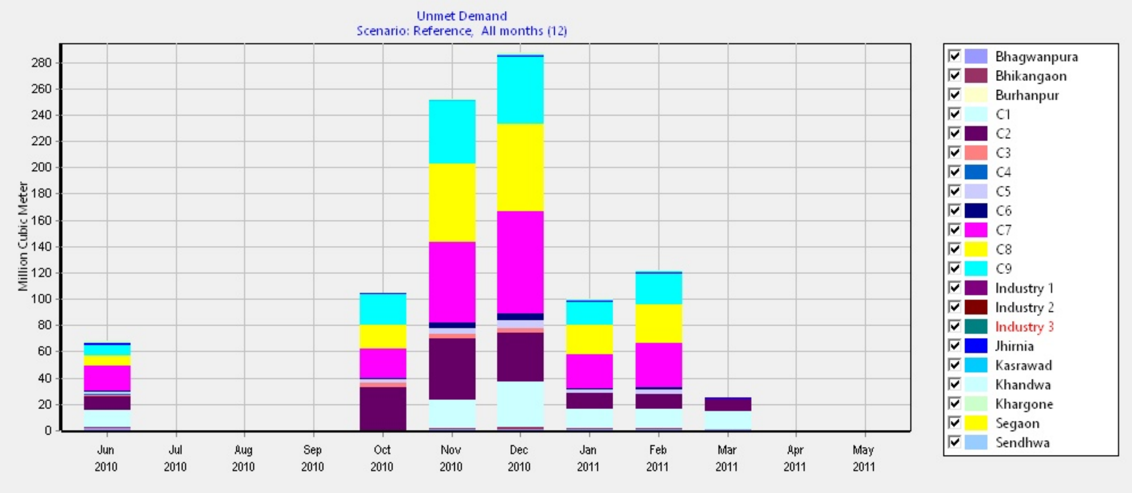

Figure 5 Monthly unmet demand.

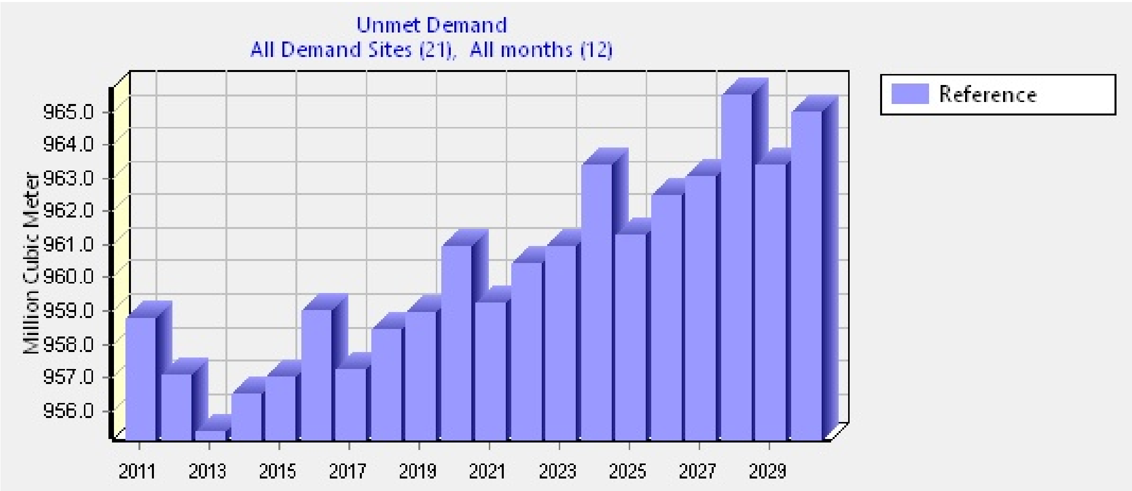

Figure 6 Annual unmet demand (from 2011 - 2030).

High population growth scenario

In this scenario the High Variant population growth rate of 1.50 % per annum for the future years is considered, the unmet demand in all administrative blocks rises from 26.16 MCM in the year 2011 to 34.86 MCM in the year 2030. The WEAP model suggested through the results that in High Population Growth Rate scenario, the total expected unmet demands are raised by 2662.46. Thousand Cubic Meters (i.e., 2.66 MCM) in the year 2030 as compared to the reference scenario. At the end of the year 2030, the expected the unmet demand could reach a maximum value of 34.86 million cubic meters as per the results generated by the WEAP model, which is 2.66 MCMs more than the unmet demand in Reference Scenario.

High industrial growth scenario

This scenario is generated to calculate possibilities of industrial development in future. The industrial growth rate is assumed as 10 % keeping all other parameters constant such as water conservation strategies, climatic conditions etc. There were 3 industries considered at the time of reference scenario but after assuming 10 % growth rate number of industries increased from 3 to 18 from 2012 to 2030. WEAP suggested through the results that in this scenario, total unmet demand was expected to increase up to 144.57 thousand cubic meters in the year 2030. There is a rise of 120.95 thousand cubic meters of unmet industrial demand in 2030 as compared to the reference scenario.

Rainwater harvesting scenario

In this scenario, a 10 % increase in the total volume of groundwater recharge is considered i.e. rainwater harvesting structures in the watershed and check dams on the streams. The cumulative effect of an increase in groundwater recharge will increase the level of the groundwater table and raise in the groundwater storage. To maintain the groundwater table at an acceptable level, it is necessary to increase the groundwater draft, to maintain the equilibrium between the recharge and draft.

Therefore, a 10 % increase in groundwater draft has been assumed. As per the analysis of the results generated by WEAP, the unmet demands are nearly around zero by the year 2030. In other words, all the water demands shall be met after some years, if groundwater recharge and draft is increased by 10 % every year. The difference is 0 in the reference year, i.e. 2011 and +290.27 in the year 2030, which indicates the increase in groundwater supply. Overall, there rise in supply delivered since groundwater recharge as well as a draft of groundwater is increased. The difference in unmet water demand from 2011 to 2030 is around 432.68 MCM after this scenario generation. Hypothetically based on the results, it can be said that the unmet water demand would be reduced after 2 or 3 decades keeping all other parameters constant. Somehow this scenario reduces the water demand to some extent in the watershed.

Additional water storage and supply structures

The proposed canal on the Veda River near Kasrawad has been placed over the Schematic of the WEAP model created for Veda River Basin. Also, one canal near Bhagwanpura block and one near Jhirnia block are considered working from 2022. Two dams of capacity 100 MCM is assumed at Kasrawad block and Khargone block. All these structures are connected to respective catchments and blocks through the supply links for both domestic and irrigation water supply. All the additional structures are assumed to work from the year 2021 onwards. A sudden noticeable decline in the unmet demands can be seen from the year 2022, the year in which the structures is pounded and is effectively supplying water to the demand sites. But as many of the demand sites cannot draw water from the reservoir and canals, the unmet demands remain in the basin

Comparison of scenarios

The Unmet Demands for all 5 scenarios, e.g., Reference, High Population Growth, High Industrial Growth, Rain Water Harvesting and Addition of Water Storage and Supply Structures have been shown in **Table 2** and **Figure 7**. The figure gives an overall outlook of the effect of different scenarios together.

Table 2 Unmet water demand for all demand sites (in MCM).

Year	Reference	High population growth	High industrial growth	Rainwater harvesting	Addition of water storage and supply structures
2011	958.75	958.75	958.75	958.75	958.75
2015	957.00	957.68	957.01	832.93	957.00
2020	960.96	962.59	961.00	746.70	960.96
2025	961.26	963.95	961.34	645.93	759.91
2030	965.00	968.87	965.14	526.08	788.28

Figure 7 also represents the relative effects of all scenarios like unmet demands increases in case of High Population Growth Rate scenario and High industrial growth scenario whereas, it decreases in case of Rainwater Harvesting and Addition of Water Storage and Supply Structures scenarios. Thus, the WEAP predicts future demands under different scenarios.

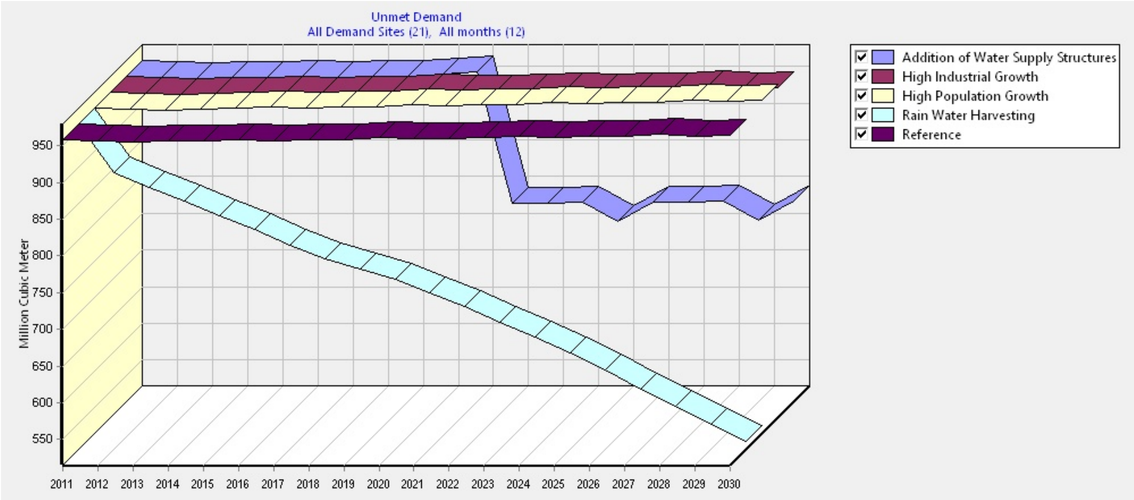

Figure 7 Comparison of unmet demand for all scenarios.

Conclusions

The demand satisfaction rates and the amount of water deficit on the river today and in the future have been obtained. The Unmet water demands in all Administrative Blocks, Catchments and Industries in the year 2011 - 2030 have been simulated which comes to be 958.754 million cubic meters in 2011 and 965.001 million cubic meters in 2030 for the reference scenario. Water demand for catchments is too high with respect to the other two (i.e., administrative blocks and industries) and almost constant for the simulation period. WEAP has a special feature of making future scenarios. In this study, the influence on water demand is shown due to the rise in the rate of population growth than the current rate. The scenario is highly probable that the population is growing every day with an increasing rate, and the new population growth rate scenario (increased exponentially) is not a complicated step to change increasing rate to 1.50 %. The Unmet water demands tend to increase from 958.75 MCM for the year 2011 to 968.87 MCM for the year 2030. As India is a developing country, considering the future development of industries in the watershed, the unmet demand in the industrial growth scenario comes out to be 144.57 thousand cubic meters which are around 6 times more than unmet demand of all industrial sites for the reference year. The unmet demand for all demand sites in the year 2011 is 958.75 MCM whereas, in 2030 it increased to 965.14 MCM. Similarly incorporating the improved groundwater recharge condition through watershed management program and rainwater harvesting structures, like contour bunds, percolation tanks, gabion structures or check dams will better satisfy water demands. These structures increase water supply sources for the basin. If artificial rainwater harvesting structures are constructed in the Veda River basin, there will be more occurrence of groundwater recharge and hence fulfilment of water demand is not solely dependent on rivers and local minor reservoirs. Also, due to the construction of groundwater recharge structures, the water is transferred directly to the ground in form of clean and freshwater, can be used throughout the year as well as for better crop yield. Consequently, groundwater draft may be increased without affecting the sustainable groundwater level. Through WEAP, this has been demonstrated by increasing the groundwater recharge and draft both by 10 %, the unmet demands reduce from 958.75 MCM for the year 2011 to merely, 526.08 MCM for the year 2030 for all demand sites. Reduction in unmet water demand is more than 45 %. The impact of the construction of proposed Indira Sagar Project canal on the Veda River near Kasrawad town has also been modelled through WEAP and found that the all the demand sites getting supply from the canal are almost satisfied, the unmet water demands are comparatively less. The unmet water demand after addition of water supply and storage structures is reduced by an amount of 170.47 MCM for all demand sites from the year 2011 - 2030. All these scenarios are important to know, and the repercussions should be considered during the planning of development projects in the future. The same climatic data for the entire simulation period was a limitation of this study. Another limitation of the study is that the model developed shows theoretical results and is applicable only for the Veda River basin only. The WEAP model has made it very easy to predict future probabilities and therefore planning could be done in a much more proactive way. After fulfilling the required objectives of this study, the recommendations based on results, should be considered for the management of Veda River basin are the implementation of groundwater recharge structures like rooftop rainwater harvesting, check dams, contour bunds etc. and adaptation of water storage and supply structures for the fulfilment of crop water requirement. Supply from Indira Sagar Dam would be the best option to fulfil water demands.

Acknowledgements

The authors would like to thank Madhya Pradesh Water Resources Department, Narmada Control Authority and Stockholm Environment Institute team for their support during this work. The authors also thanks to all those peoples supported in this research work either directly or indirectly.

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