Efficient Reservoir Operation in an Arid Region with Extreme Hydrologic Flows: A Case Study, Oman's Largest Dam

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Abstract

Wadi Dayqah dam (WDD) is still not operating, and its operation targets are not yet fixed. Arid hydrology and the presence of new users require a new look at this dam's operation plan. The updated and optimal operation plan of WDD is the central research gap about this dam. In this study, to fill this gap, Water Evaluation and Planning (WEAP) is used to model the system and six scenarios, including the reference target of 35 MCM per year suggested goal that considers different operation targets as well as a modification to water system configuration by the addition of an upstream dam is suggested. This model is validated and used for 37 years of historical flow. Results show that the reference scenario is less than 55%, and an annual goal of 15 MCM has a maximum of 85% supply reliability. Adding a 20 MCM upstream dam can increase reliability by 5%. It is recommended that to enhance the economic aspects of the dam, suitable energy generation schemes are studied with unique configurations, such as pumped-storage hydro, as well as studying the other sizes of upstream dams that can contribute more to water distribution and energy generation.

Keywords: WEAP model; Wadi Dayqah dam (WDD); Optimal reservoir operation; Water resources planning; Variable hydrology

1 Introduction

Wadi Dayqah dam (WDD), since its completion in 2009, is still not operational, and its initial suggested water demand target of 35 MCM may be exposed to modifications according to the existing hydrologic and water demands development conditions. The extreme and ephemeral nature of the Wadi Dayqah basin hydrology brings up this critical question to decision-makers: What is this dam's reliable capability for water supply to downstream demands. Optimal dam reservoir water resource allocation is essential for efficient and sustainable environmental health and development (Agarwal et al., 2018; Nematollahi et al., 2021). The capability of adequate water resources management requires correctly understanding the physical system and the inclusion of hydrological procedures (Mustafa & Yusuf, 2012; Yazdandoost et al., 2021; Nematollahi et al., 2022). Climate change is an essential factor affecting the efficiency of water resource systems (Hong et al., 2016). Modelling is capable of providing an integrated and comprehensive framework for assessing water resources and policy-making for them, including the dams. Water Evaluation and Planning (WEAP) software is successfully applied worldwide in many water resource systems with different hydrologic conditions. To establish modelling for efficient water resources management and allocation in extreme hydrological situations, the WEAP software can be considered a powerful tool.

The WEAP model has been extensively utilized for managing water resources, particularly in extreme hydrological conditions such as drought and flood (Yates et al., 2005; Roberto & Matthew, 2007). The WEAP model has been used in the literature to study the models of the saline lake (Raskin et al., 1992), river basins (Levite et al., 2003), groundwater and surface water (Yates et al., 2005), reservoirs (Hagan, 2007), and dams (Mounir et al., 2011). These applications have revealed that the WEAP model is an effective tool for water, agricultural, and municipal systems modelling for single and multiple catchments networks to handle water resources in different hydrological conditions (Daniyal et al., 2017; Suryadi et al., 2018). Hence, applying the WEAP modelling for water allocation in extreme hydrological conditions can be considered a significant advancement in each water system.

Several studies have been proposed in the literature on hydrological modelling using the WEAP model to simulate the catchment procedures. For this purpose, different WEAP models have been generated corresponding to different study areas such as Krishna, India (Bharati et al., 2008), Seybouse valley, Algeria (Berredjem & Azzedine, 2017), Mara river basin, Kenya (Metobwa et al., 2018). However, although the Wadi Dayqah dam (WDD) reservoir exists in Oman, its operation plans and water supply targets are not decided yet. Furthermore, the hydrological flow to this dam has an ephemeral nature with extreme conditions varying between 3.15 to 467 MCM. In such conditions obtaining an optimal reservoir operation plan based on highly varying hydrological conditions can be well modelled and analysed by well-developed tools such as the WEAP software.

In this study, WEAP software is used to model the optimal monthly operation of the WDD and find the optimized water demands that maximize the reservoir operations efficiency in terms of water supply reliability. In sum, the main goals of this study were delineated as the following:

(1) Modelling the WDD reservoir operation by the WEAP model,

(2) Statistical analysis of annual Wadi Dayqah (WD) catchment flow,

(3) Defining the water allocation scenarios for WDD with the WEAP model,

(4) Obtaining reservoir operational rule curves for the WDD.

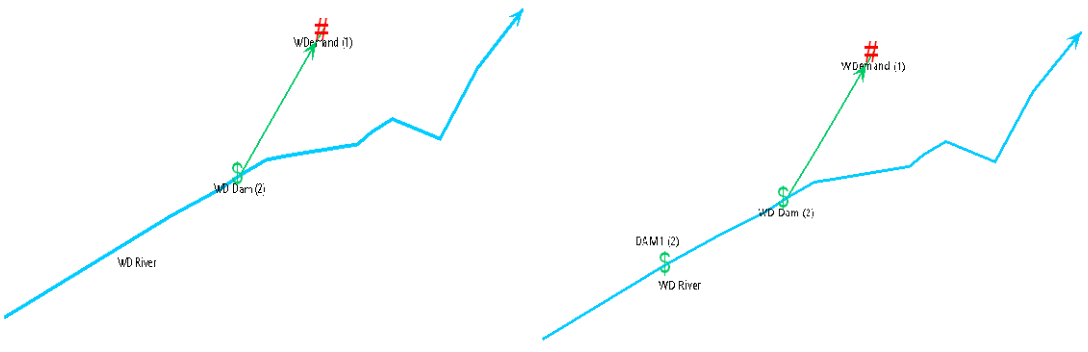
2 Methodology

The proposed methodology endeavoured to address several concerns related to the WDD operations through modelling by the WEAP:

- In the current condition, how is the efficiency of the WDD in fulfilling its operation?
- How could the WDD operational efficiency be improved by modifying the water demands or water system configuration, such as adding an upstream dam?
- What are the contributions of the effective reservoir operations for the WDD in the current and modified conditions?
- How much demand is achievable with good reliability in the current and future conditions?

2.1 WEAP Modelling

Figure 1 illustrated a schematic view of the WDD reservoir and its operational zones in the WEAP. This figure showed the WDD reservoir operation model, wherein monthly reservoir operation was modelled. In this study, all the priorities were assumed as one during modelling for the dam and demand for the WDD and the WD two dams' system except the priority of filling the WDD for the two dams' system to avoid filling water without a specific requirement. In addition, it was hypothesized that the consumption for the demand was 100%. Moreover, the total capacity of 100 and 20 MCM were assumed for the WDD and upper dam. In addition, in modelling the WEAP model for the WDD, the normal water year was assumed for the dam with the storage capacity of 100 MCM, considering the initial storage of 25 MCM in 1983. Finally, the maximum flow in the transmission links was hypothesized as 3.55 MCM in the presented model.



(a) **(b)**

Fig. 1: Schematic view of the Wadi Dayqah reservoir and its operational zones in the WEAP for **(a)** the WDD and **(b)** the WD and upstream dams' system

2.2 Problem Statement

Wadi Dayqah is a multi-purpose reservoir in Oman, and its primary objectives are flood management and water supply. The capability of the WDD to satisfy its future water requirements is essential to plan wisely for water resource allocation. To this extent, the modelling tools coupled with the scenario analysis approach can be essential for effective management strategies considering different hydrological situations. Therefore, applying the WEAP model as a robust modelling technique in conjunction with a scenario analysis technique results in an applicable water resources management for the WDD.

This study endeavoured to obtain the optimal reservoir operations for the WDD under different hydrological conditions based on the WEAP modelling. This paved the road for the reservoir planners to assess the effects of various possible future management approaches for the optimum releases from the dam, considering the constraints and priorities in extreme conditions.

Scenarios

Through this modelling, the scenarios were defined to determine the most reliable water level to fulfil the water demand requirements, considering the variations in the safe yield of the reservoir due to different inflow. These scenarios could be noted as follows:

(1) Reference scenario: Simulating the existing design of the dam considering the main

application of water supplying as 15, 20, 30, and 35 MCM per month,

(2) Increasing demand scenario: Considering the increase in the demand resulting in rising hydraulic releases of up to 45 and 55 MCM per month,

(3) Upstream dam construction scenario: Hypothesizing an upstream dam building to increase the performance of the WDD to enhance the water supply reliability (This scenario became critical if the water supply reliability was very low in a reference scenario).

2.3 Water Demand

The water demand requirement for domestic utilization, hydropower generation, environmental demands, and irrigation allocations should be defined in this model (Figure 2). Annual water demand scenarios are considered as 15, 20, 30, 35 (reference scenario), 45, and 55 MCM with the same monthly distribution as the reference scenario. This range of water demands helps to understand the safe annual yield of WDD and if there is any possibility to develop the water demands to higher values.

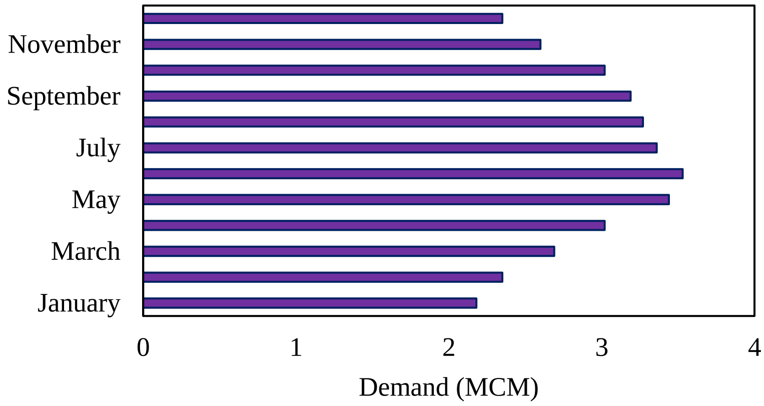


Fig. 2: Monthly demand for the Wadi Dayqah dam

3 Study Area

The WD catchment is located in the Al Hajar Ash Sharqi Mountains, wherein the wadi flows from the village of Tul down to Daghmar, and discharges to the coastal alluvial catchment (Figure 3). The WDD, built on 2010, is the principal flood controller for the WD flows while supplying drinking water for Quriyat and Muscat in Oman, which water supply system is still under construction (Figure 3). The average surface flow through the Wadi Dayqah from 1978 to 2005 was 50.97 million m^3 per year, so a reliable water yield of 35 MCM per year was assumed for the WDD.

The WDD reservoir has a volume of 100 million m3, equal to two years of average flow. This reservoir has an area of 350 hectares, a gross yield of 35 Mm3 per year, and an average stream flow of 50.97 MCM per year. The WDD water supply system consists of modern water treatment and supply system. This water allocation system takes water from the WDD reservoir to Quriyat Wilayat and other Wilayats of Muscat (Wadi Dayqah dam book, 2006).

Fig. 3: The Wadi Dayqah dam's location

4 Results and Discussion

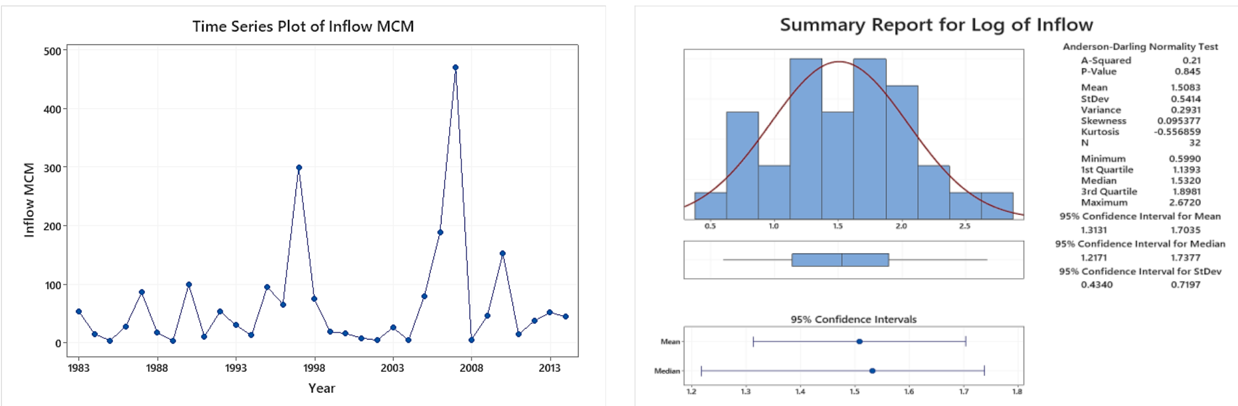
In the proposed WEAP model, the reference scenario could be utilized to validate the model considering the:

- Inflow statistical properties and downstream flow must be related.
- If water demand is low, the reliability of the water supply must be high.

4.1 Statistical Analysis of Inflow

In the proposed The statistical behaviour of flows to clarify that in arid or semi-arid catchments, the routine method of dam reservoir design may not apply was delineated in the following using Minitab. Figure 4 (a) was the time series of annual flows, including high and low amounts. This analysis indicated that Log(Mean) = 1.5083. This value revealed that the Mean was equal to 32 MCM, which was different from the arithmetic mean, 52 MCM by data of 1978-2003 or 66 MCM by data of 1978 – 2014.

Figure 4 (b) indicated that flow followed a log-normal distribution. According to this statistical analysis, the Median was 1.532; that was the Log(Q), so that Q = 34 MCM. In addition, when the Mean was 1.5083, Q = 32.2 MCM, much less than the considered Q-ave = 50 MCM for the dam design.

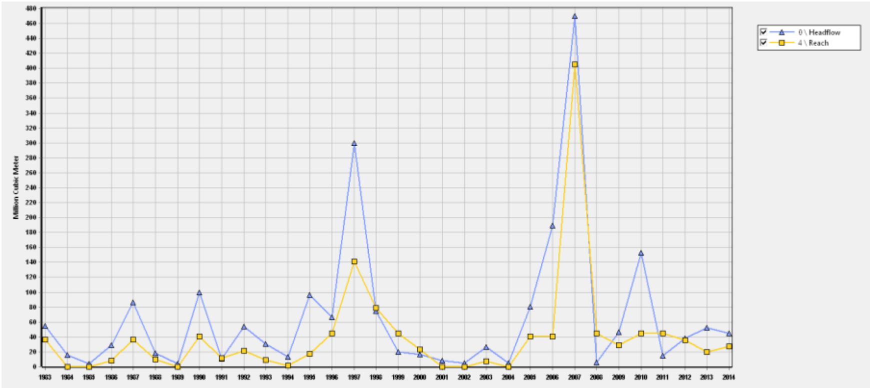


(a) (b)

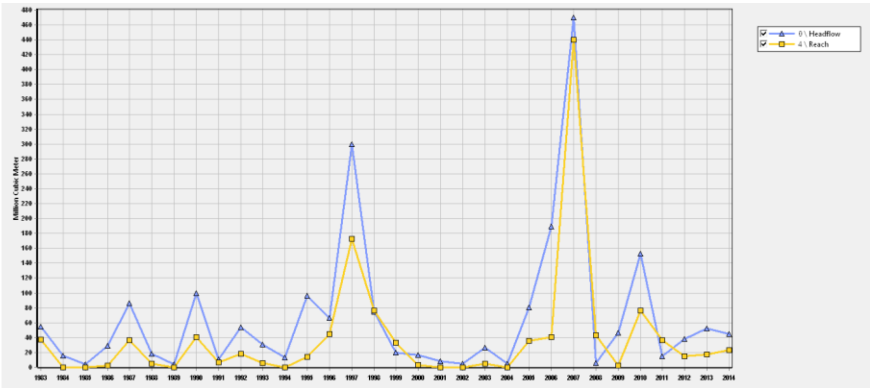
Fig. 4: Statistical analysis of WD catchment flow at Dagmer Station, **(a)** Time-series plot (MCM), **(b)** Log of inflow

4.2 Head Flow

Figure 5 showed the head flow after the WDD downstream. Some changes in flow were generally addressed as reservoirs regulating the flow. However, the statistical properties of both flows, such as the mean, were different due to water consumption. On the other hand, the other properties did not change meaningfully, which can be an indicator of model validity since the statistical properties of both head flow and downstream flow were within the range of head flow used as a validation for this model. Figure 6 indicated that the Wadi release to the sea was reduced and could be consumed for different purposes through the WDD and its upstream dam.



(a)

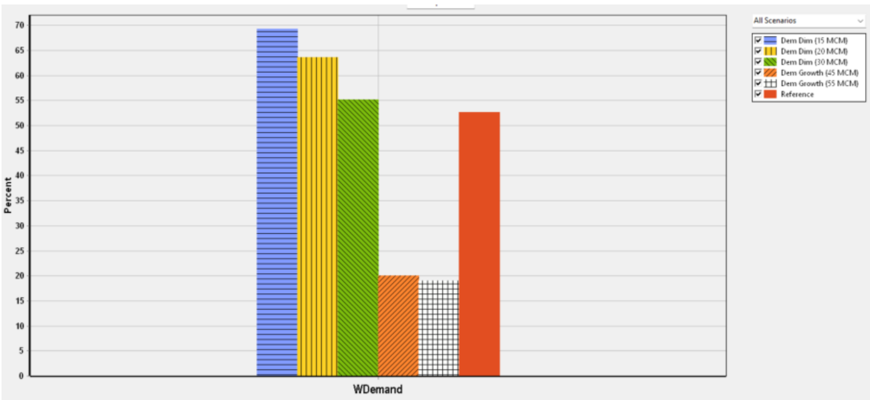


(b)

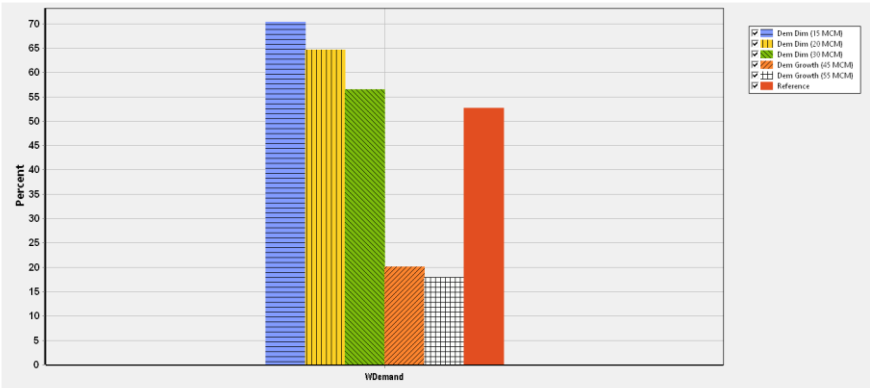
Fig. 5: Headflow at WDD downstream for **(a)** the WDD and **(b)** the WD two dams' system

4.3 Demand Analysis

Figure 6 showed the reliability of water demand supply since the reliability of water supply to demands is the primary measure of the efficiency of the WDD system. This figure approved that higher reliability was achieved with less demand, which was logical as another confirmation for model validity and validation. Therefore, this figure proved the effectiveness of the present modelling in meeting the water demand requirements.



(a)



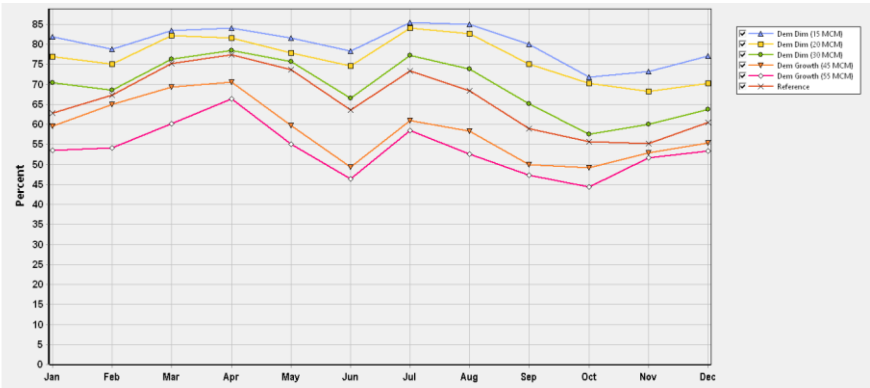
(b)

Fig. 6: Upstream optimal reservoir storage for **(a)** the WDD and **(b)** the WD two dams' system

Notably, adding an upstream dam increased the water supply reliability by 5% maximum. However, to determine whether this 5% was meaningful, an economic analysis of the water supply that included the value of water was required to determine that this 5% increase justified the consideration of the upstream dam as a serious suggestion.

4.4 Water Supply

Figure 7 illustrated the percentage of water supply each month, showing that each month for each scenario met a considerable percentage of demand from the reservoir. The annual demand of 15 MCM had the highest reliability of 85%, while the annual demand of 55 MCM had the lowest reliability of 45%.



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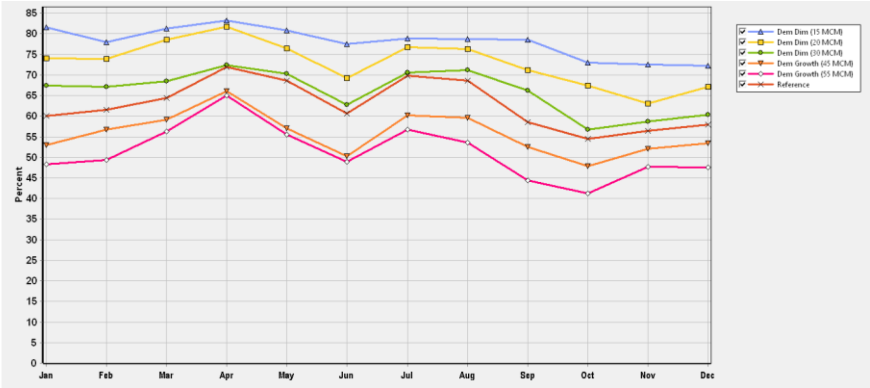

(b)

Fig. 7: Water Supply **(a)** the WDD and **(b)** the WD two dams' system

5 Conclusion

In this study, optimal operational rules have been determined considering present and future optimal water allocations from the WDD using the WEAP model. Model analysis showed that water demands in the range of 15 to 55 MCM could not be supplied with 100% reliability, and maximum reliability belonged to 15 MCM with 85% reliability. Furthermore, this study showed that adding an upstream 20 MCM dam on the main Wadi drainage at 2 Km upstream could increase the water supply reliability by 5% maximum.

It is recommended that economic energy generation alternatives be added to this system to make the reservoir operation more economical by the special scheme for upstream dam suggested with a power plant located at WDD Lake to provide high net head or inclusion of pumped-storage dams at high elevations.

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