Flood Retention Dams for Controlling Flash Floods in Oman

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ABSTRACT:

Oman is an arid country located next to the Indian Ocean from where several cyclones originated in the last century, e. g., the devastating cyclone Gonu in 2007. Since then the Oman authorities in form of the Ministry for Regional Municipalities and Water Resources launched a flood protection campaign which resulted in the construction of several large dams. Still many flood retention dams are in the planning stage, some are more or less ready for construction.

Wadi Dayqah and Fulaij Dams are among the spearhead projects which were recently completed. The RCC dam on Wadi Dayqah was already loaded by a major flood which proofed its functionality.

Corresponding to the local conditions in Oman design, construction and operation of flood retention dams face several challenges such as extreme temperature differences, large and quick flash floods through the canyons, strong sedimentation, and, usually, dry basins. From first hydrological analyses, the preparation of the final and detailed design, construction works and supervision to operation measures these special conditions show their influence. The special challenges for dams in Oman are illustrates by selected case studies, e. g., Wadi Al Khawd dam which is located close to the Muscat airport and which is in design review stage.

1 INTRODUCTION

Oman is an arid country located next to the Indian Ocean from where several cyclones originated in the last century, e. g., the devastating cyclone Gonu in 2007. Since then the Oman authorities in form of the Ministry for Regional Municipalities and Water Resources launched a flood protection campaign which resulted in the construction of several large dams. Still many flood retention dams are in the planning stage, some are more or less ready for construction.

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2 BASICS OF OMAN

2.1 *Location and country*

The Sultanate of Oman is located west of the Indian Ocean embraced by the Arabian Gulf and Gulf of Oman in the north and the Arabian Sea in the East and South. The surface area amounts to 309,500 km² with a coastline of 3,165 km. Oman is bordered by Yemen, Saudi Arabia and the United Arab Emirates.

Most of the area is desert or desert-like. Settlements and infrastructure is generally located close to the Northern coast line, the Al Batinah plain, and very south in Salalah. The capital is Muscat. In the year 2018 approximately 4.8 million inhabitants were living in Oman. The Sultanate includes some exclave areas such as Musandam, Madha, the Island Masira, etc.

More information is given in MRMWR (2009).

2.2 *Climate and rainfall*

During summer the average temperature reaches maxima up to 41 to 44 °C, which is strongly depending on the location. E. g., the average temperatures in the very south in Salalah "only" are between 24 to 30 °C. Along the coast humidity is quite high showing maxima of 80 %. In Oman the rainfall is among the lowest in the world as the evaporation counts to the strongest worldwide. The annual evaporation is between 1,700 to 3,000 mm which leads to an evaporation rate between 80 and 95 % in consideration of the annual rainfall which is 100 mm on average in Oman. Hence, Oman is counted to the semi-arid to arid countries where precipitation is much less than evaporation. The rainfall shows a volume of approximately 19,250 Mm^3. 15 % of the rainfall recharges the aquifers, 5 % is lost to the sea.

The climate of Oman is firstly dominated by the Indian Ocean and the warm stream of the Gulf of Oman as well as the warm winds reflected by the Iranian high mountains and the mountain ranges in Oman itself, in the north Hajar Al Gharbi and the Dhofar mountains in the south.

The south of Oman experiences also monsoon influence (see MRMWR, 2011).

3 **HYDROLOGY, WATER RECOURCES AND FLOODS**

3.1 *Surface water and runoff, water use*

The rainfall run-off or surface water is estimated to be about 1,050 to 1,400 Mm^3 in Oman (MRMWR, 2009). Approximately 20 % of the run-off is lost to the sea. The available water is stored to 65 % in groundwater and 35 % in surface water.

Approx. 80 % of the available water is used for agriculture. Due to the country's development the water demand is expected to increase steadily.

3.2 *Groundwater*

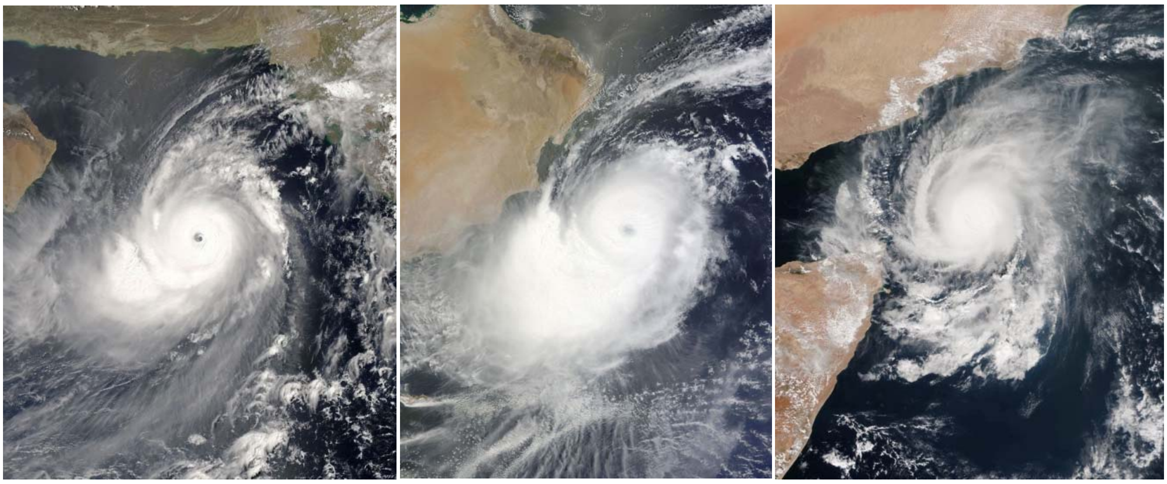
Major groundwater flows in Oman occur along the Al Hajar al Gharbi and the Dhofar mountains towards the sea in the Al Batinah coastline. The recharge volume per year is estimated to be 1,300 Mm^3/year. Due to the problems with the groundwater resources the Sultanate constructed many groundwater recharge dams, mainly in the North Batinah plain, to overcome the effects of groundwater exploitation and seawater intrusion.

The water demand in Oman is covered by 92 % by groundwater withdrawal in 2008 (Kathry & Helmi, 2008). The withdrawal is approximately 1,131 Mm^3/year.

The water balance shows a deficit of approximately 378 Mm^3/year due to intensive groundwater exploitation which is not covered by the recharge rate.

3.3 *Floods*

The floods in Oman are dominated by cyclones which are originating over the Indian Ocean (Figure 1). The cyclone Gonu generated discharges with an annual reoccurrence period of locally T = 500 to 1,000 a and higher (see Haselsteiner, 2011; Schmid & Dix, 2017).



Cyclone Gonu, June 2007; max. winds 235 kmh/h

Cyclone Phet, June 2010; max. winds 155 kmh/h

Cyclone Megh, Nov. 2015; max. winds 205 kmh/h

Figure 1. Selected satellite images of cyclones during the last decades causing floods in Oman.

For the Wadi Dayqah Dam a PMF flood discharge of 18,400 m^3/s was determined basing on a catchment area of 1,700 km^2. This results in a specific discharge rate of $q = 10{,}000$ $l/(s*km^2)$ which is extreme in consideration of worldwide experiences documented, e. g. in Wundt (1965). Depending on the local conditions the spillways of dams are usually designed for a T = 10,000 a flood discharge, the PMF discharge or 0.5*PMF (MRMWR, 2013).

4 CHALLENGES

4.1 *Climate change*

A changing climate shows also an effect on the flood discharges. Especially for the development of cyclones worldwide the increase of the average temperature results in stronger storms with a more likely occurrence (see Figure 2). The temperature and the number of cyclones are also expected to increase in the future.

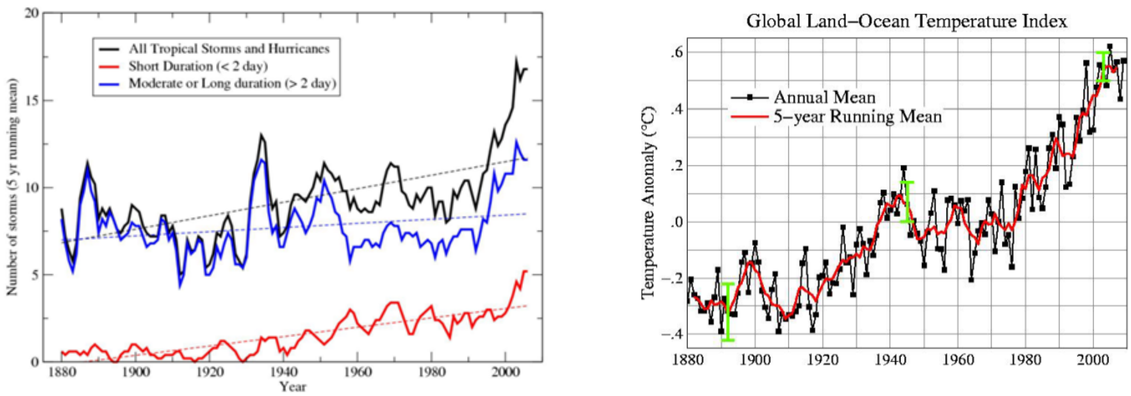


Figure 2. Development of the number of storms worldwide and global temperature anomaly since 1880 (see also Knutson et al., 2010).

In consequence the hydrological and hydraulic design has to be continuously checked and, if required, the spillways need to be upgraded. Additionally, the occurrence of flood events is likely not to decrease so that flood retention and protection projects need to be realized with a high priority.

4.2 *Temperature*

In Oman, the temperature difference between night and day and summer and winter are extreme. For the design and construction of concrete structures this fact required special treatment of the concrete, mainly cooling. For a rapid and smooth placement of RCC structures the concrete technology is critical, cooling is essential in order to avoid uncontrolled cracking.

Temperature strain of the concrete after hardening due to temperature changes need to be covered by an adequate joint design.

4.3 *Sedimentation*

The sediment load is quite huge in Oman. Thus, the reservoirs are stressed by sedimentation after each flood incidents. During design the expected sedimentation should be considered for the definition of the dead load of the reservoir.

The sedimentation plays a major role for groundwater recharge dams since the sediments are decreasing the reservoir volume also because the sediments should stay in the reservoir in order to keep away from downstream recharge channels. As for flood protection/retention dams the flood volume should be not decreased by sediments in order to guarantee the flood protection function.

Thus, the dead storage should be defined in consideration of the operation period of the dam. At least, the dead storage should cover an operation period of more or less 20 years.

Observation within reservoirs document the strong sedimentation processes in Oman (see Haselsteiner, 2011; Al-Maktoumi et al., 2014; Rajendran, 2015).

4.4 *Geology and earthquakes*

The mountains in Oman are young in regard with geological perspectives. The mountains may also show ophiolitic rocks as well as sedimentary rocks such as limestone and sandstones. IN the north Batinah region a deep alluvial fan is overlaying the base rock. The wadis are usually filled with gravels and show steep abutments which may also be vertical.

The earthquake thread is induced by the collision of the Arabian and the Indian plate. The Arabian plate is moving north so that along the Gulf of Oman thrust and subduction zones occur and along the eastern coastline the Owen fracture zone. The earthquake risk is increasing to the north so that it is highest in Musandam and lowest in Salalah. Considering the world earthquake risk map only the northern region is showing an earthquake risk which may result in pga values of 1.0 g and more.

Sea earthquakes may also be a reason for tsunamis so that there is also a tsunami risk at the northern and eastern coastline of Oman.

4.5 *Flash Floods*

The flash floods are generated by heavy rainfalls originating mainly from huge cyclones which are coming from the Indian Pacific. The strong intensity of rainfalls exceeding 500 mm/day is the reason that the floods show rather the characteristics of mudflows carrying a considerable sediment load. Modelling of flash floods in order to predict its characteristics is therefore a scientific challenge (e. g. Al-Rawas, 2008).

Although the meteorological processes over the Indian Sea can be observed and predicted the flood evolves quick after rainfall starts. Only few hours or less are left after strong rainfall starts until the flood reaches the wadis in the settled areas along the coastline.

This shows also consequences on the construction diversion and the flood management during construction. Also during floods a manual adjustment of hydraulic facilities of dams seems not to be possible.

4.6 *Groundwater Recharge / Seawater Intrusion*

As already mentioned decreasing groundwater levels and seawater intrusion endanger groundwater resources of Oman. The deficit created by the water consumption cannot be balanced by up-to-date recharge measures.

Hence, as soon as permanent or temporary reservoirs are established the effects on groundwater have always to be considered. Especially, when groundwater recharge dams are located downstream of larger flood retention dams the operation scheme of the large reservoirs needs to be adapted to the requirements of groundwater recharge. The combination of large reservoirs in the mountainous areas with groundwater recharge dams in the lower plains, where recharge is required, looks like a favorable combination as described in Haselsteiner (2011).

Basics and more information of groundwater recharge especially in the Sultanate of Oman are given Haimerl (2004), FAOUN (2009), and Abdalla et al. (2013).

4.7 *Ageing*

Due to the extreme climatic conditions the ageing of applied materials is much taking place much faster than under moderate climate conditions. The high temperature variations stress all materials and lead to brittleness, cracking, shrinkage, chemical processes, etc.

In order to overcome the effects of ageing adequate design and construction including the proper choice of the dam type and materials are essential as well as a long-term maintenance concept (see Haselsteiner, 2018; ICOLD Bulletin 93, 1994).

For coast near dam structures also the salinity in the air may show an effect on steel structures which has to be taken into consideration during design and operation.

5 **LARGE DAM PROJECTS**

5.1 *General*

The Ministry for Regional Municipalities and Water Resources (MRMWR) initiated several studies for flood protection and groundwater projects: The studies were prepared for wadis, catchments or certain regions, such as the North Batinah Plain (see Strobl & Schmid, 1997a,b,c; Haselsteiner, 2011; Agelles, 2012; MRMWR; 2012).

Selected, characteristic dam projects are briefly summarized below. A map of Oman shows the locations of the selected projects (Figure 3).

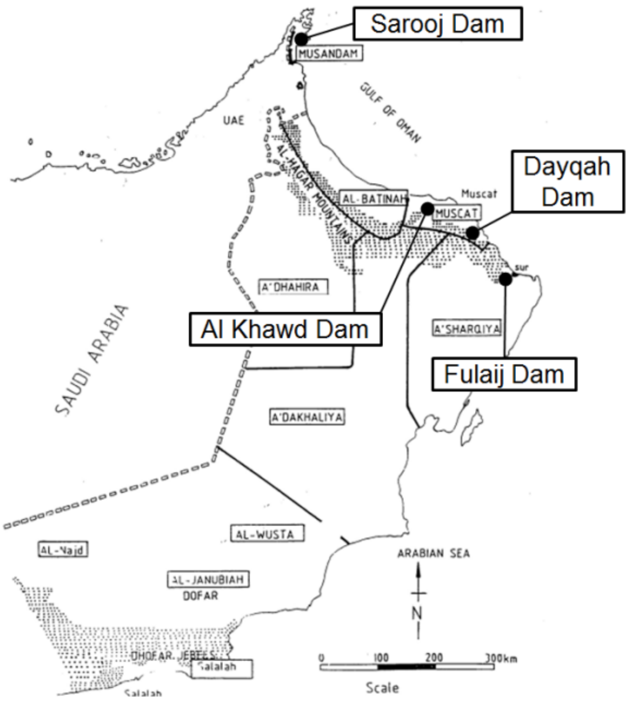


Figure 3. Map of Oman with locations of selected dam projects.

5.2 *Sarooj Dam*

The Sarooj Dam is located in Madha on the way to Musandam. It is a groundwater recharge dam with a height of over 20 m and a length of approximately 150 m. The PMF shows a discharge of 2,500 m³/s so that the spillway is loaded by a specific hydraulic load of 25 m³/(s*m).

The dam itself shows a cut-off wall similar to that one used in Wadi Hawasinah dam (see Strobl & Schmid, 1997c). Thanks to favorable foundation and underground conditions a subsoil sealing was not applied.

An operation tower with two outlets guarantees the downstream discharge of 2.0 m³/s for groundwater recharge purposes. The estimated groundwater recharge efficiency is considered to be over 90 % (see Kleist et al., 2005).

5.3 *Wadi Dayqah Dam*

Wadi Dayqah Dam is located south east of Muscat close to the city of Sur. The annual run-off is 52 to 60 Mm³/year. The storage capacity is 100 Mm³ (Strobl, 2013; MRMWR, 2011).

The dam shows a main dam and a saddle dam. The main dam type is a gravity dam in form of a roller compacted concrete (RCC) dam. The dam length is 410 m, the dam height is 75 m. The saddle dam is a rockfill dam with a vertical cut-off wall. The length is 360 m and the height is 48 m.

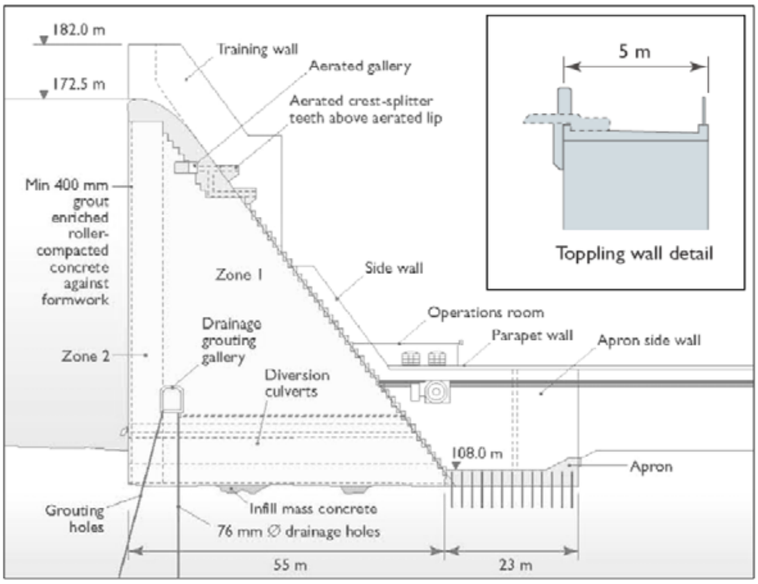


Figure 4. Cross section through the Wadi Dayqah RCC Dam with the toppling crest elements (taken from Hieatt et al., 2010).

The cross section in Figure 4 shows a typical gravity dam which hosts the spillway. For RCC dams a proper foundation is required which is usually reflected by strong rocks. Usually, the foundation conditions determine the choice between concrete and embankment/rockfill dam.

The design flood discharge is 18,400 m^3/s which reflects the PMF. The dam spills over the overflow crest with subsequent stepped spillway and stilling basin. The flood discharges were reevaluated after the Gonu cyclone in 2007 with the result that the flood discharges increased so that also dam layout needed to be adapted. During the cyclone PET in 2010 the dam was impounded. The documented situation during the impoundment justified the adaptation of the spillway capacity (see Strobl, 2013, Al Harty et al., 2010; Hieatt et al., 2010).

Wadi Dayqah Dam is a multipurpose dam showing a permanent reservoir. Reservoir water is used for irrigation and drinking water (Figure 5).

Figure 5. View of Dayqah Dam from the left abutment (taken from RMD, 2014).

5.4 *Fulaij Dam*

For flood protection and flood retention purposes a 1.2 km long and rockfill dam with asphalt core and a milled cut-off wall for the underground sealing was constructed. The aim of the regional flood protection project is mainly to protect the city of Sur and decrease the flood discharge by placing flood retention dams upstream in the wadis.

The dam is 1.2 km long and approximately 23 m high. The dam shows two types, a rockfill/embankment dam and a concrete dam. The design flood discharge is 4,000 m³/s. The dam spills over the concrete dam as well over the embankment dam (see Figure 6). Asphalt core embankment or rockfill dams count to the state of the art practice in consideration of safety and economic aspects. In comparison to concrete dams the complete concrete procession and curing is not required and the asphalt core provides a reliable and durable safety element which does control the seepage conditions. Additionally, those types of dams can also bear a certain level of settlements and deformations without showing damage.

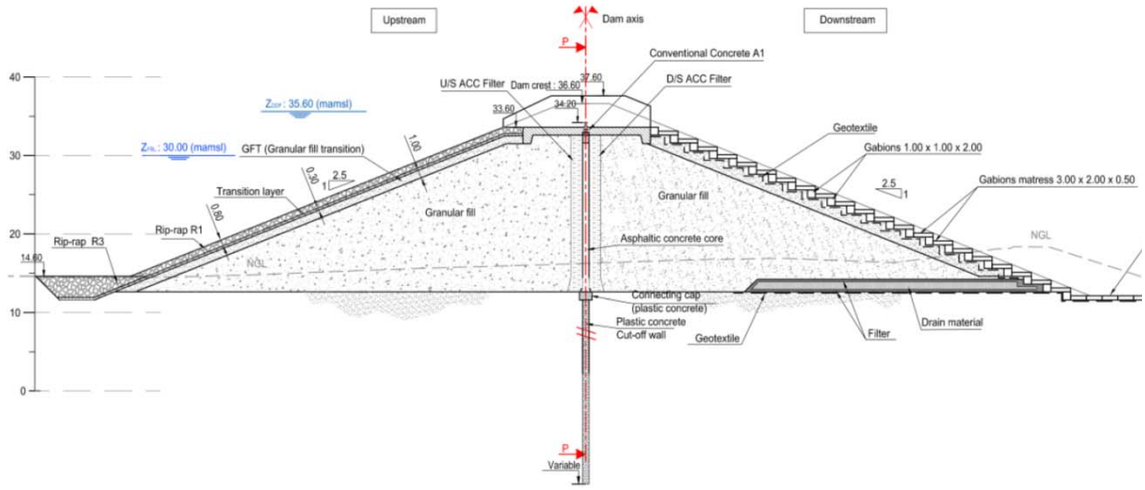


Figure 6. Cross section through the embankment dam with gabions on the downstream slope of the dam.

The costs for the construction were around 100 Mio. €. The dam was constructed during 2014 and 2017 within 44 months /STRABAG, 2017; see Figure 7).

Figure 7. Arial view of Fulaij Dam (taken from STRABAG, 2017).

5.5 *Wadi Al Khawd Dam*

Al Khawd dam is located close to the village Al Khawd which is close to the airport Muscat. The flood protection dam is upstream of the existing flood groundwater recharge dam Al Khawd.

The dam scheme shows a main dam with a concrete RCC dam and a rockfill dam with an asphaltic center sealing and three smaller saddle dams. The main RCC dam is 62 m high and shows and length of 580 m. The main rockfill dam is 46 m high and shows a length of 590 m (MRMWR, 2011). The design floods are Q_T=100a = 1,600 m³/s and Q_{PMF} = 11,675 m³/s.

The special situation of the Al Khawd flood retention dam some kilometers upstream of the existing groundwater recharge dam Al Khawd grants the possibility to adjust the operation scheme of the big reservoir for the sake of the groundwater recharge efficiency of the small groundwater recharge dam. Additionally, some of the sediment load can be hold back in the large reservoir.

The dam is in project stage. The final design is completed. The estimated costs for the project are approximately 100 Mio. €.

6 CONCLUSION

The Sultanate of Oman is object of flood events. It has to be expected that these events will be stronger and more frequent in the future. Hence, for controlling floods and mitigating the inherent risks, large dam projects with large reservoirs are required in order to retain the floods.

Large dam projects are under preparation or in execution. Mainly RCC concrete dams and embankment/rockfill dams with asphaltic core are applied as state of the art dam types. A special problem is generally the large flood discharges which lead to high specific hydraulic loads on the spillways. Hence, concrete chutes are frequently applied.

Since many wadis are splitting the mountains and locally strong rains may cause high discharges almost everywhere along the coastline many flood retentions dams are required. In combination with local flood protection measures such as wadi/river training works and local levees or flood protection walls the efficiency of those projects is increasing.

Since Oman is a well developing country the risks and damage potential are not expected to decrease so that the responsible MRMWR will continue to realize large dam project in order to mitigate the flood risks in the future.

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