京都大学防災研究所年報 第 62 号 B
DPRI Annuals, No. 62 B, 2019

Reservoir Sedimentation at Wadi System: Challenges and Management Strategies

Mohamed SABER, Sameh KANTOUSH, Tetsuya SUMI, Yusuke OGISO(1), and Tahani ALHARRASI(2)

(1) OC Global, Tokyo, Japan
(2) Graduate School of Engineering, Kyoto University

Synopsis

In this paper, current challenges of reservoir sedimentations are presented along with our achievements to overcome such struggles for long term sustainable management of sediments in dry reservoirs are also addressed. There are several problems of sedimentation in wadi system including decreasing reservoir storage capacity, affecting the groundwater recharges (sediment clogging), increasing the disaster risk of flash floods, and downstream environmental impacts. Two field surveys on Dec 2017 and Sept, 2018 were conducted for Wadi Mijlas in Oman in order to study the sedimentation issues and its impacts on the reservoir capacity and infiltration processes. Several measures have been implemented such as pedon analysis, collecting sediments samples, drone survey, infiltration tests were conducted. The sedimentation volume at the reservoir along Wadi Mijlas was estimated from the sedimentation measure bars installed in the reservoir before the dam constructions. Sediment transport modeling and infiltration modeling were successfully conducted. The results showed that the recharge rate was adversely affected by sedimentation.

Keywords: Wadi Flash Floods, field survey, sedimentation, infiltration, sediment transport modeling, arid regions

1. Introduction

Reservoir sedimentation is a global challenge, especially in arid regions when the monitoring and information are missing as well as the lack of effective management techniques. In arid and semi-arid regions, a large proportion of sediment yield and erosion are formed due to flash floods (Walling, D.; Kleo, A. 1979). However, a little attention paid to sedimentation impacts associated with flash floods in such regions, especially in the Arab regions (the most hyper aridity conditions). Sedimentation process is controlled by many factors including geological and topographical features of the basins, land uses and soil types variability, intensity and frequency of extreme storms, and climate change and human impacts.

Previous researches and studies have been done on Wadi flash floods modeling, forecasting and management (Saber, 2010, Kantoush, et al., 2011, Saber et. Al., 2013, Sumi, et al., 2013, Abdel-Fattah et al., 2015, Abdel-Fattah et al., 2017, Saber and Yilmaz 2018), but addressing of sedimentation issues is still missing in wadi basins. Therefore, in this study, the current challenges of sedimentation, approaches and management strategies are presented. The main objective of this paper is to answer the raised key questions: How can we understand the current circumstances and impacts of reservoir sedimentation?, What are the current and available sedimentation management techniques? How can we overcome the current

Fig. 1 Recent Mekunu Cyclone (May 25, 2018), (a) JAXA Global Rainfall Watch for the cyclone, (b) the resulting damage in southern Oman (Salalah).

challenges for long-term sustainable management in arid regions?

Recently, flash floods are becoming more frequently and devastating in arid regions, especially under the climate changes and sedimentation impacts. Oman had experience with severe flash floods such as (Guno cyclone, June, 2007 and Phet cyclone, June, 2010). For instance, the Guno cyclone (Q=900 m3/s) caused 50 fatalities and 3.9 billion USD of economic losses (Al Barwani, 2015). A great damage in infrastructures, hosing, and agriculture lands are recorded from Guno cyclone. Also, Mekunu cyclone happened on May 25-26, 2018 (Fig. 1) with great damage, especially in southern part of Oman (Salalah). It was much more powerful than previously recorded events in southern Oman, and has extended into the neighboring countries as well. It reached category 3 as reported by the MRMWR. The cyclone endured from May 23 to May 27 with total rainfall of about 617 mm, and the maximum rainfall of about 505 mm in two days (May 25 and 26, 2018) as recorded by the rain gauges.

Wadi systems in arid regions (Fig. 2a) are not only characterized by extreme disasters (e.g., flash floods, drought) but also a lack of monitoring networks and integrated management strategies for water as well as sediments. Flash floods have become more frequent, especially in connection with extreme events like cyclones (Fig. 2b). In Oman, mitigation structures for flood control and groundwater recharge have been installed. However, issues of sedimentation were underestimated, leading to environmental problems due to reservoir sedimentation (Fig. 2c). This was examined in field investigations in December 2017 and September 2018. In Oman as an arid country, they have already installed many mitigation structures for flood control and groundwater recharge, but they did not consider the sedimentation issues, therefore, there is a real environmental problem due to the reservoir sedimentation (Fig. 2c) as we have observed in our field investigation on Dec. 2017 and Sept. 2018. However, Oman is one of the countries that could experience critical sedimentation volumes (Fig. 3a) by year 2050 (ICOLD, 2009), the current conditions of sedimentation exhibit that have already a real problematics of sedimentation at many reservoirs (Fig. 3b).

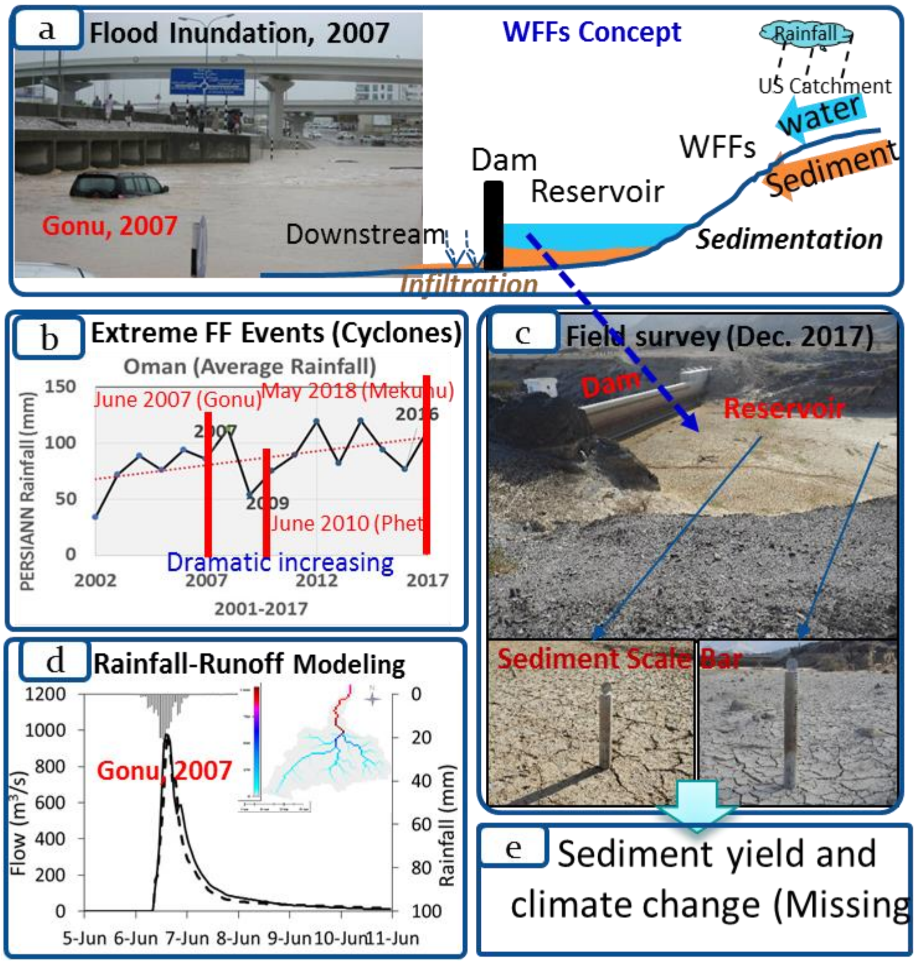


Fig. 2 The Wadi flash flood concept (a), problematics (b), achievements (c & d), and gaps (e).

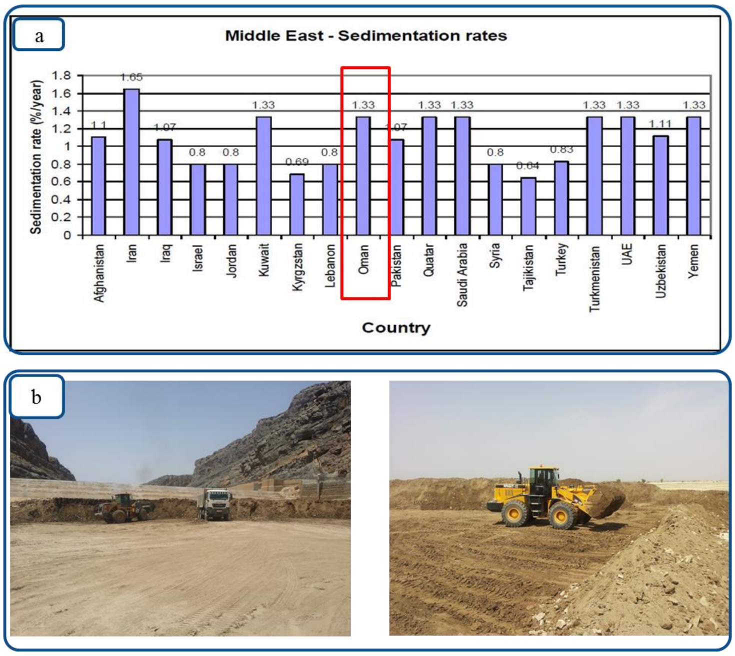


Fig. 3 Actual and predicted sedimentation in the Middle East (ICOLD bulletin 2009) (a), reservoir sedimentation at Wadi (right photo), and Wadi (Left photo) (b).

2. Motivation and Objectives

Sedimentation is the most serious technical problems in reservoirs management especially in arid regions with increasing extreme flash floods. Why sedimentation is quite important in wadi basins?, the answers are listed below:

- The lack of previous studies especially in regard of their impacts on reservoir and infiltration.
- The deterioration of dam ability to store water influencing on its functions for floods protection.
- Decreasing the infiltration and consequently affecting the groundwater recharge.
- Increasing the disaster possible impacts of wadi flash floods.
- In dry environment as wadi basins, the aforementioned problem are expected to be more serious and destructive than the perennial rivers with the impacts of climate changes.

Therefore, assessment the adverse impacts of sedimentation at wadi basins is desperately crucial to bring forth a secured integrated water and sediment management. The main key scientific questions are:

- What is the impact of climate change on extreme rainfall events?;
- How to predict sediment yield based on understanding flash floods spatiotemporal variability and sediment dynamics?,
- What are the impacts of sedimentation on the infiltration processes?

In order to address the raised questions and overcome the related problems of WFFs in arid regions, we are conducting this research work in order to understand sediment yield and dynamics, in addition to impacts of sedimentation on the infiltration processes in dry reservoirs.

3. Study Area

Wadi Mijlas in Oman is located near Qurayyat cityat 55 km southeast of Muscat at (23°8’46-23°20’46N, 58°26’34-58°56’58E) (Fig. 4). Two dams were constructed in this basin in 2011, Aserrin Up dam and Aserrin Down dam (Aserrin I and Aserrin II). Wadi Mijlas area is about 700 km2.

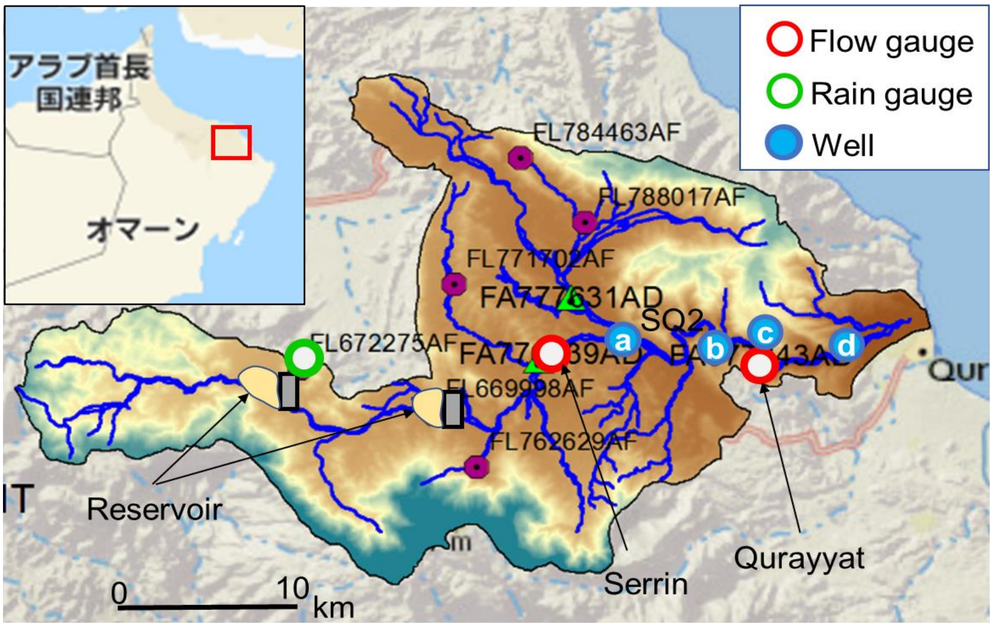


Fig. 4 Study area of Wadi Mijlas in Qurayyat and the location of the Aserrin I and Aserrin II dams.

This basin was chosen for two reasons. First of all, it is a big challenge that there are few hydrological data such as rainfall and discharge, which leads insufficient understanding of the hydrological characteristics in the arid regions. From this reason, a field survey was conducted in Oman, where relatively monitoring systems are installed well among the arid regions. because both dams (Aserrin I and Aserrin II) are relatively new, which were constructed in 2011. There were just less than 10 intense rainfall events in Qurayyat basin after the construction of both dams in 2011. Therefore, it was possible to understand the relationship between rainfall and sedimentation by analyzing the layer of deposited sediment in dam reservoir. In dry areas, monitoring sedimentation data is rarely conducted and sometimes completely not considered. Also, it is difficult to grasp the amount of sediment accumulation because sediment is removed without measurements irregularly. As this dam is built, it is not long enough to remove sediment, and it is a dam suitable for measuring the amount of sediment deposition.

Most of the previous studies were conducted on Wadi Samail, but in this study, we are deeply focusing on Wadi Mijlas as one of the most important wadis in Oman and also the most affected one during Gonu and Phet cyclones. The government installed several rain gauges and wadi gauges which would be very useful for the model calibration and validation.

4. Reservoir sedimentation

There are several problems of sedimentation based on our field investigations and survey in wadi system (Fig. 5) including: 1) decreasing reservoir storage capacity (Fig. 5a), 2) affecting the groundwater recharges (sediment clogging) (Fig. 5b&c), 3) increasing the disaster risk of flash floods, and 4) downstream environmental impacts. Due to the infrequent occurrence of flash floods in the past, the decision makers and planners did not take in their consideration the sedimentation issues. Therefore, currently, the flash floods become more frequent and devastating with huge sedimentation yield causes a real challenge of sediments in most of the reservoirs.

One of the most effective measures for floods and droughts is groundwater recharge dam. Figure 6 shows the recharge dam in Oman, Al Amerat Heights Dam. The length of the dam is 5896 m and Maximum height is 23 m, storage capacity 22.4 Mm3. This dam is earth fill/rockfill dam with plastic concrete wall in the embankment. In figure 6, the right side is upstream and the left side is downstream where is recharge zone. Usually, recharge dam is low and wide like Al Amerat Heights Dam. These hydraulic structures have functions of flood control groundwater recharge.

The main challenges for such recharge dams are, the sediment clogging (See figure 5b & c). The accumulation of fine sediments in dam reservoirs is a major problem as siltation reduces water storage capacity, and furthermore causes clogging on river bed, reducing infiltration rate. Due to this clogging in dam reservoirs and recharge zone, the ability of recharging ground water decreases gradually.

5. Field survey

Two field surveys in December 2017 and September 2018 were conducted for wadis Mijlas and Samail in Oman in order to study sedimentation issues and its impacts on the reservoir capacity and infiltration rates. Several measures have been implemented such as wadi channel leveling, sedimentation Pedon to study the vertical layers of sedimentation at the reservoir by collecting sediments samples for further lab analysis, and detecting of flash floods marks. Additionally, drone survey, infiltration tests, and field questionnaire about flash floods were conducted. The sedimentation volume at the reservoir along wadi Mijlas was estimated from the sedimentation measure bars installed in the reservoir before the dam construction.

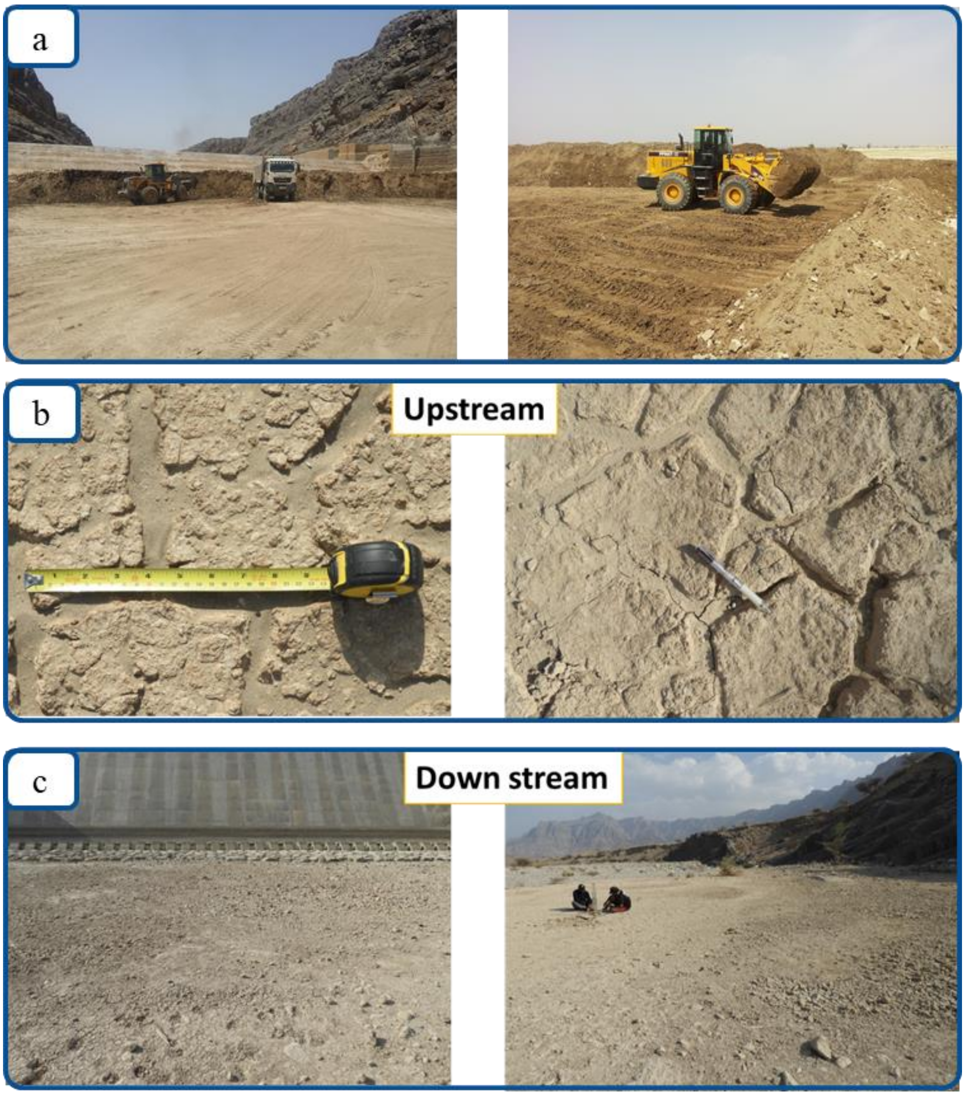


Fig. 5 (a) Reservoirs are full by sediments in some wadi in Oman, and Sediment clogging at upstream (b), and downstream (c).

Fig. 6 Al Ameret Heights Dam was taken by UAV, Kyoto University team in 2018.

5.1 Sedimentation measures and pedon analysis

Several sedimentation bars were installed by the Ministry of Regional Municipalities and Water Resources in Oman. We measured the level of these bars and estimated how much sediments were deposited from 2011-2017. Figure 7 shows the distribution map of measurement bars location and survey location. Three holes (pedon) were dug along the central line of the reservoir at equal intervals (Fig. 7) We could able to distinguish about six soil layers with different thickness (Fig. 8) and characteristics such as grain size and vegetation content. The sediment thickness on the central line

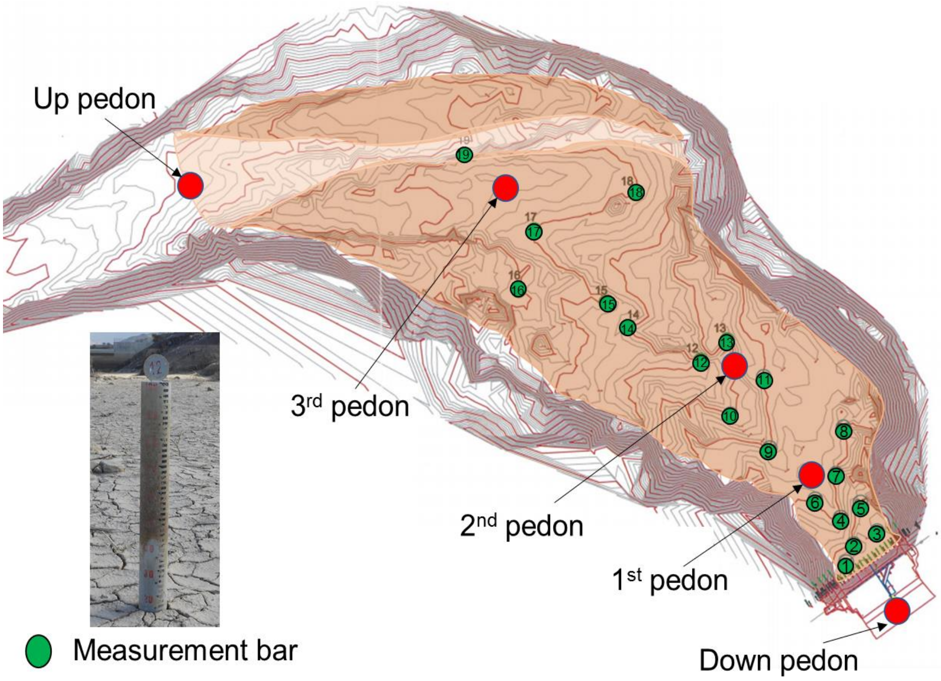


Fig. 7 Distribution map of measurement bars and location of Pedon analysis in Aserrin II dam (Kyoto University Team, Field Survey on 2017 and 2018)

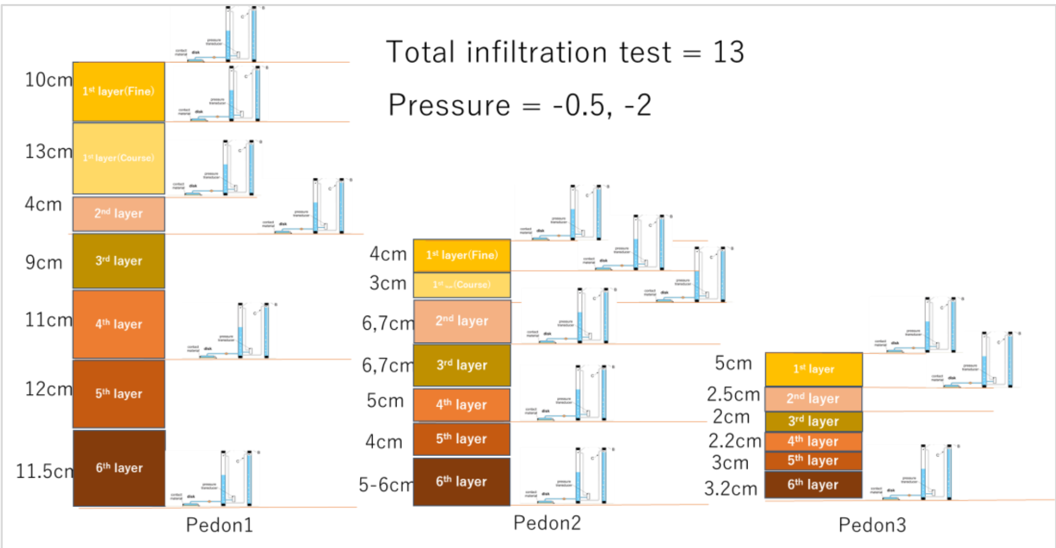


Fig. 8 The soil layers thickness and locations of the Places where infiltration tests were conducted at the three pedons and soil layer thickness under pressures of -0.5, -2 at Asserin II dam

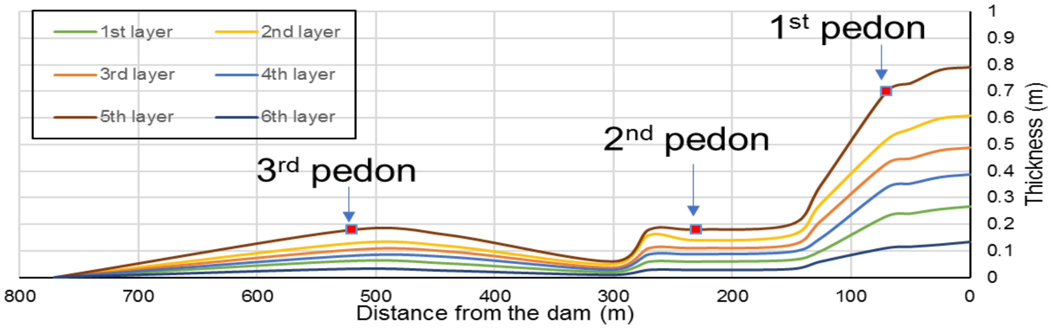


Fig. 9 Sediment thickness along the central line of the reservoir crossing the pedons.

in the reservoir was estimated based on the identified layers at the three pedons and the installed measurement bar, for instance the sediment thickness reaches to about 1 m at some locations. Figure 9 shows the layer thickness. The first layer is clearly separated with coarse sediment at lower part and fine sediment at upper part. These layers were analyzed in particle size using the hydrometer method for each layer. From hydrometer method, soil texture of 1st fine layer, 2nd layer, 3rd layer, 4th layer and 5th layer is Silt, 1st coarse layer is Sandy loam, and 6th layer is Silty loam. From this, fine sediment such as silt and clay consist of sediment in the reservoir

5.2 Infiltration test

In this study, the SMS tension infiltrometer was used to measure the unsaturated flow of water into soil accurately at the three pedons and several layers vertically (Fig. 8).

The infiltration test were conducted at the three pedons in order to assess the impact of sediment layers on the recharge process. At Pedon 2, the results of infiltration test and grain size analysis shows the relation between soil texture and saturated hydraulic conductivity. Ks decreases at the layers from up to down with depth (Fig. 10). It is found also that Ks is declining when the grain size is decreasing. The previous study of Mazaheri (2012) also showed agreement finding with this results that soil particle distribution affects the infiltration rate. The longitudinal change of Ks along the tested sites is observed (Fig. 11). This reveals the impact of sedimentation on the infiltration rate. Also, Ks of the surface layer decrease from upstream to downstream, which is also related to the soil texture. Further analysis for all the layers by using Infiltration model to simulate such changes are still running.

5.3 Drone survey

Over two days, we have conducted drone surveys using Phantom 4 pro at different locations and sites (Figs 12a) including (Assarain Dam Up, Assarain Dam Down, Al-Sawaqim , the monitoring station, old monitoring Station along Wadi Mijlas, and the new Proposed Dam and also at Wadi gauge station site. The reservoir of Asserin Dam up was

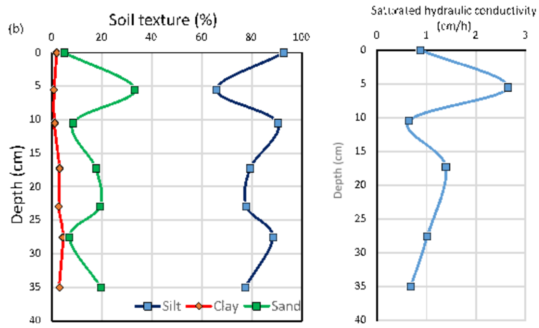


Fig. 10 Soil texture and saturated hydraulic conductivity at 2nd pedon).

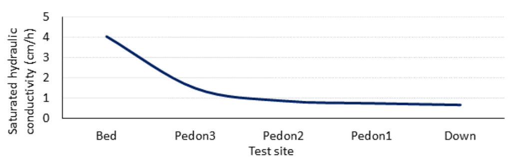
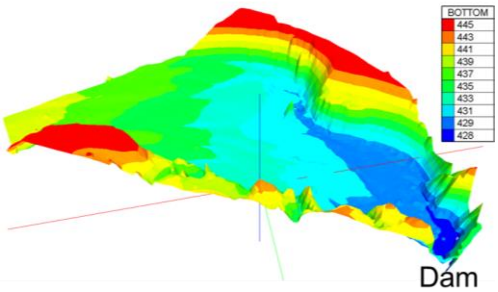


Fig. 11 Longitudinal change of saturated hydraulic conductivity

(a)

(b)



(c)

Fig 12. Satellite image showing the sites for Drone Survey at Wadi Mijlas, Oman (a), Drone photos at Assarin Up Dam, Wadi Mijlas, Oman (b), and High resolution Digital Elevation Model (DEM) generated from UGV's will be used as input topographic for sediment transport modeling (c)

selected to develop the bathymetry DEM (Fig.12b & c). The drone images were analyzed to produce very high resolution Digital Elevation Model (DEM) at the reservoir (Fig.12b & c), about 0.5 m spatial resolution that will be very useful to enhance the topographic data inputs for the hydrological model. The drone images was processed by Photo Scan software. This DEM are very crucial to enhance the input topographic maps for the hydrological models, and consequently to reduce the model uncertainty related to topographic data acuaracy. This results will be used for the future modeling of sediment transport models and also for future sediment changes over the target basins by comparing this results with the future results to assess how much the deposited sediments for any future flash flood events.

6. Sediment Transport Modeling

TELEMAC-SISYPHE is used to simulate the sediment transport at Asserin Dam II. The simulation results of sediment transport in the 2017 event is shown in Fig. 13. Simulated sediment deposition of the 2017 event is concentrated near the dam, which same as measured deposition.

7. Effect of the sedimentation on recharge

Hydrus 1D Model was used to simulate the infiltration rates considering different scenarios. The effect of sedimentation on groundwater recharge is discussed at several cases including no sediment layers, three sediment layers and seven sediment layers. Situation of seven sediment layers is present reservoir sedimentation. Situation of no sediment layers is before dam construction. In the case of no sediment layer, free drainage at bottom start at 20 hour and infiltration rate reaches 14.6 (cm/hour). At 46 hours, it shows that it decreases rapidly. Original bed soil is gravel bed and has high saturated hydraulic conductivity. That's why water

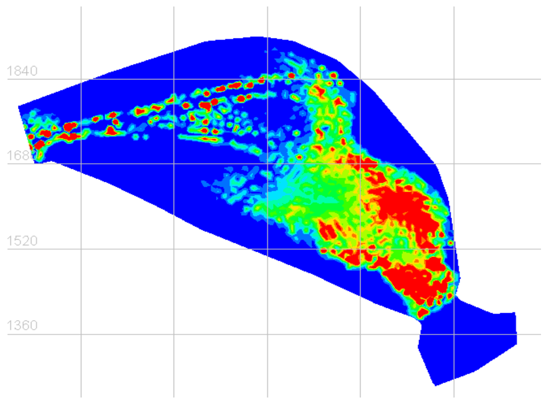


Fig. 13 simulation results of sediment transport in the 2017 event.

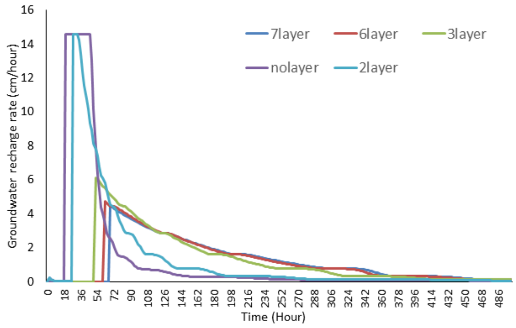


Fig. 14 Simulated groundwater recharge rate with different layers.

goes through soil rapidly. In the case of three sediment layer, free drainage at bottom start at 50 hour and infiltration rate reaches 6.3 (cm/hour), and then decrease gradually. In the case of seven sediment layers, free drainage at bottom start at 66 hours and infiltration rate reaches 4.4 (cm/hour), and then decrease gradually. Start of recharge of seven layers' case is delayed compared with cases of three sediment layers and seven sediment layers (Fig. 14).

8. Conclusions

In this paper, the current challenges of sedimentation in arid regions were discussed and reported. An integrated approach to understand the sedimentation in dry reservoirs including field survey, numerical modeling is proposed. The results of field investigation were discussed in order to understand the sedimentation impacts and also to validate the numerical models along with satellite data to assess the sediment yield in arid regions. The results of pedon analysis showed that there are 6 sediment layers were accumulated since the dam construction in 2011. High resolution DEM was generated from UAV images, and it was used as input for the sediment transport modeling. Sediment transport modeling using TELEMAC was successfully done. The infiltration tests and simulation using Hydrus 1D Model shows that the sediments layers reduce the recharge rates in the reservoir. Additional applications using the same approach at different dry reservoirs are recommended.

Acknowledgements

This research was funded by the International Collaborative Research, grant number 30W-01, and General Collaborative Research, grant number 30A-01, internal funds of Disaster Prevention Research Institute (DPRI) at Kyoto University, Japan. The support and provided facilities for the field investigations and data collection from Sultan Qaboos University and the Ministry of Regional Municipalities and Water Resources is highly appreciated.

References

Abdel-Fattah, M., Kantoush, M. and Sumi, T. (2014): Integrated Management of Flash Flood in Wadi System of Egypt: Disaster Prevention and Water Harvesting. Annuals of DPRI, Kyoto Univ., No.58B, pp. 485-496.

Abdel-Fattah, M., Kantoush, S., Saber, M., & Sumi, T. (2016): Hydrological Modelling of Flash Flood at Wadi Samail, Oman, Annuals of DPRI, Kyoto Univ., No.59B, pp. 533-541.

Abdel-Fattah, M.; Saber, M.; Kantoush, S.A.; Khalil, M.F.; Sumi, T.; Sefelnasr, A.M. A hydrological and geomorpho-metric approach to understanding the generation of wadi flash floods. Water, 9, 553, 2017.

Al Barwani, A. (2015) : Flash Flood Mitigation and Harvesting Oman Case Study, First International Symposium on Flash Floods (ISFF), Kyoto, Japan.

ICOLD, C. Sedimentation and sustainable use of reservoir and river systems. Draft ICOLD Bulletin. Sedimentation Committee. Google Scholar 2009.

Kantoush, S. A., Sumi, T., Kojiri, T., Saber, M., Elshennawy, I., Awad, H., & Sefelnaser, A. (2011): JE-HydroNet: modern methodologies for the management, monitoring and planning of integrated water resources in the nile delta of Egypt. In Proceedings of the 34th World Congress of the International Association for Hydro-Environment Research and Engineering: 33rd Hydrology and Water Resources Symposium and 10th Conference on Hydraulics in Water Engineering (p. 3928). Engineers Australia.

Saber M., Habib E. (2016) Flash Floods Modelling for Wadi System: Challenges and Trends. In: Melesse A., Abtew W. (eds) Landscape Dynamics, Soils and Hydrological Processes in Varied Climates. Springer Geography. Springer, Cham.

Saber, M. (2010): Hydrological Approaches of Wadi System Considering Flash Floods in Arid Regions, PhD Thesis, Graduate School of Engineering, Kyoto University.

Saber, M., Hamaguchi, T., Kojiri, T., Tanaka, K., & Sumi, T. (2015): A physically based distributed hydrological model of wadi system to simulate flash floods in arid regions. Arabian Journal of Geosciences, 8(1), pp. 143-160.

Saber, M., Hamagutchi, T., Kojiri, T., and Tanaka, K. : Hy-drological modeling of distributed runoff throughout com-parative study between some Arabian wadi basins, Annual J. of Hydraulic Eng., JSCE, Vol. 54, pp. 85-90, 2010

Saber, M.; Yilmaz, K.K. Evaluation and Bias Correction of Satellite-Based Rainfall Estimates for Modelling Flash Floods over the Mediterranean region: Application to Karpuz River Basin, Turkey. Water, 10, 657, 2018.

Sumi, T., Saber, M. and Kantoush, S. A. (2013): Japan-Egypt Hydro Network: science and technology collaborative research for flash flood management. Journal of Disaster Research, 8(1), pp. 28-36.

Walling, D.; Kleo, A. Sediment yields of rivers in areas of low precipitation: A global view. Proceedings... The Hydrology of areas of low precipitation 1979.

(Received June 17, 2019)