E310

Impact of Sedimentation of Recharge Dams on Water Resources Management: overview from Oman

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Abstract:
In the Sultanate of Oman, 174 dams have been constructed as of 2021 for different purposes: flood protection (3 dams), recharge (56) and surface storage (115) with a total storage capacity exceeding 423 million m^3. Recharge dams represent one of few engineering structures to harvest flashfloods water in wadi systems in arid zones for augmenting the limited water resources. These reservoir dams proved their efficiency in recharging the underlying aquifer systems and also relatively control seawater intrusion in coastal aquifers in Oman provided that abstraction of groundwater is properly managed (Abdalla and Al-Rawahi 2014, Al-Kindy 2004). However, due to the high velocities of runoff water, large quantities of eroded sediments are often transported from the catchments and deposited in the reservoirs of the dams (Prathapar & Bawain, 2014, Alataway et al., 2019, Fouli et al., 2015, Al-Saqri et al, 2015, Al-Ismaily et al, 2013, Casas et al., 2021, Djuma et al., 2017, Luo et al., 2020, Sumi et al., 2022, Mohammadzadeh-Habili and Khalili, 2020, and Zaidi et al., 2020). Accumulation of surface sediments impacts many hydrological properties of dam's reservoir area, including reduced infiltration and deep percolation rates, higher water loss via evaporation, and ultimately lower aquifer recharge and stronger flood peaks. (Prathapar & Bawain, 2014, Alataway et al., 2019, Fouli et al., 2015, Al-Saqri et al, 2015). Al-Saqri et al., (2015) found that about 3.4 Mm^3 of sediments have been deposited in the Al-Khoud recharge dam over 30 years since construction of the dam. This resulted in decrease of the infiltration rate by 10 times compared to that for original soil. Prathapar and Bawain (2014) found that increase in the thickness of the sediments in dams delays commencement of recharge and reduces recharge volumes for a Sahalanowt recharge dam in south of Oman. Infiltration capacity has decreased by at least two orders of magnitude (from 16 to 0.18 cm/h) during 17 years since its construction. It appears that macro-pores are being clogged by vertically translocated fine sediments with percolating water.

Not only the silted reservoir bed is affected, but also the recharge basin downstream the dam receives pulses of suspended sediments after each major flashflood. The downward (in the vertical, *z*-direction) translocation of fine particles into the coarse-texture vadoze zone causes progressive and essentially transient clogging (see e.g. Yin et al., 2021 for a pore-scale description of such clogging) of the interstitial space, which reduces the saturated hydraulic conductivity $K_s(z)$ (see e.g. experiments in Reddi et al., 2000, Sato and Kuwano, 2015, Yousif et al., 2017). Our field experiments, we found that saturated hydraulic conductivity (K_s) drop by 10 times compared with areas not experienced overflow and sedimentation by the flashflood (Al-Saqri et al., 2015, Faber et al., 2015).

We have experimentally examined the vertical infiltration curves for a multilayered-heterogeneous reservoir beds of "dry dams" in arid regions (Al-Maktoumi et al., 2015). The non-monotonic, wiggling of the infiltration rate dependencies of silt and sand contents along the soil profile, within the shallow vadose zone, are corroborated by infiltration tests and pore-scale models (Al-Maktoumi et al., 2015). The discovered "reversed" textural profiles and non-monotonic cumulative infiltration curves have intricate hydro-engineering implications, e.g. we observed that the runoff water, released from the dam, instead of a fast vertical infiltration, forms a shallow quasi-horizontal Darcian flow that out-seeps further downstream into local topographic depressions and contributes to undesired runoff-evaporation. This type of ephemeral but intensive quasi-horizontal seepage is similar to the phenomenon of "subsurface stormflow" usually studied in hillslope hydrology. This adversely affected the recharge rate.

Reservoir sedimentation threatens the stability and safety of the dams due to hydro-ecological interplay (Kacimov and Brown, 2015). The slopes of the embankment are supported with gabions (Kacimov and Brown, 2015) that have large mesh openings, acting as “corridors” and hosting settled suspended soil particles and seeds of plants transported to the dam by the wadi current, after each flash flood and reservoir filling. The rip-rap on the dam slopes serves as a mulch which reduces evaporation from the very wet dams’ upstream and downstream shoulders and clay core of the dam. Fine textured materials are characterized by high water-holding capacity that intercepts and retain the exfiltrating water, and hence serves as a moisture supply source that supports the growth of lush vegetation, which thrives on the slopes of the embankment. A vegetation strip has been observed on the slopes of several embankments of recharge dams in Oman, upon a number of cycles of torrential rains and temporary filling of the dam reservoir. The on-slope vegetation is interpreted as the footprint of a long-lasting storage of pore water in the embankment. Hydrologically, a small-size groundwater mound within the permeable shoulder of the embankment transpires and creates a eco niche for intensive propagation of plant roots into the clay core that may cause the collapse of the dam (Kacimov and Brown, 2015). The responsible governmental entity set a monitoring program to uproot this vegetation from the embankment slopes and to reinforce the core with a concrete wall to avoid possible damage to the dam structure. This illustrates that the woody specie of vegetation may play a dual role: when a tree is far away from the dike, the roots are beneficial for increased aquifer recharge, albeit when a tree or shrub is on the embankment slope, its impact can be deleterious for the hydraulic structure.

Several earth-filled recharge dams have the toe (blanket) drains in the embankments. The deposited sediments gradually clog these drains. We studied seepage to unclogged (Kacimov et al., 2022) and clogged drains. We assessed how 2D Darcian flows in the embankment induce spatially non-uniform hydraulic gradients and transient suffusion. The fine soil fractions of the "pristine" embankment dam (including its clay core) are washed away downstream and deposited as an “invisible cake” on the top of the drain. That defeats a standard geotechnical design and action of the drain filter. Under high hydraulic gradients in the drain's vicinity, the fine particulates are entrained into the body of the initially coarse material such that the "internal colmation" occurs. On the interface of embankment zones of contrasting K_s, a complex 2-D refraction of the vector field of Darcian velocity takes place (Kacimov and Obnosov, 2012) with the local I value far exceeding the safe limits against suffusion. Using sandbox experiments, such interfaces were explored for drain clogging regimes at different reservoir water levels (hydraulic head drops between the reservoir and tailwater). A dramatic rise of the phreatic surface in the embankment, affected by clogging of the toe drain, was detected, albeit accompanied by a drop of the seepage flow rate. The former is insidious for dam's stability because the phreatic surface can outcrop on the tail-water slope, which may collapse.

It is noteworthy that even large earth-filled dams, e.g. the Orowille one in the USA are now experiencing regimes of reservoir filling similar to classical recharge dams in Oman. Indeed, prolonged droughts in Arizona, California, Nevada and other states result in “drying” the reservoirs, which – after rainy years – get rapidly filled up. That causes severe hydraulic stresses on the porous structures and their collapses. Novel analytical and numerical modeling techniques were used for studying seepage in the embankments experiencing such extreme and not anticipated hydrological impacts (Kacimov et al., 2020).

Recharge dams in Oman (and in arid areas in general) are important hydraulic structure as a water harvesting system and also for protection against flood hazards. They will play even more role and becomes more important due to expected impacts of climate change on water resources in this region. Hence, more focused research to be carried out to manage the silted reservoirs so we sustain the functions of the dam. For example, estimation of the sediments load brought in by flashflood is important to manage the sedimentation rate at the reservoirs. Currently, we are running a field experiment in collaboration with DPRI, Kyoto University, Japan to measure sediments load in flashfloods.

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References
Alataway A, El Alfy M (2019) Rainwater harvesting and artificial groundwater recharge in arid areas: case study in Wadi Al-Alb, Saudi Arabia. J Water Resour Plan Manag 145:05018017

Al-Ismaily S., Al-Maktoumi A., Kacimov AR., Al-Saqri S., Al-Busaidi H., Al-Haddabi M., (2013) Morphed block-crack preferential sedimentation in a reservoir bed: a smart design and evolution in nature, Hydrological Sciences Journal, DOI: 10.1080/02626667.2013.838002

Al-Saqri S., Al-Maktoumi A., Al-Ismaily S., Kacimov A., Al-Busaidi H, (2015) Hydropedology and soil evolution in explaining the hydrological properties of recharge dams in arid zone environments. Arabian Journal of Geosciences, 9 (1), ISSN 1866-7511. DOI 10.1007/s12517-015-2076-0

Al-Maktoumi A., Kacimov A., Al-Ismaily S., Al-Busaidi H., Al-Saqri S. (2015) Infiltration into two-layered soil: the Green-Ampt and Averyanov models revisited. Transport in Porous Media, 109:169–193. DOI:10.1007/s11242-015-0507-8

Bouwer H., Ludke J., Robert C. Rice. (2001) Sealing pond bottoms with muddy water. Ecological Engineering 18: 233–238.

Casas, J.D.H., Kalwa, F., Walther, M. and Rausch, R., 2021. Stormwater harvesting in ephemeral streams: how to bypass clogging and unsaturated layers. *Hydrogeology Journal*, 29:1813–1830.

Djuma H, Bruggeman A, Camera C, Eliades M, Kostarelos K (2017) The impact of a check dam on groundwater recharge and sedimentation in an ephemeral stream. Water 9:813.

Faber S., Al-Maktoumi A., Kacimov A., Al-Busaidi H., Al-Ismaily S, Al-Belushi, M. (2015) Migration and deposition of fine particles in a porous filter and alluvial deposit: laboratory experiments, Arabian Journal of Geosciences, 9 (4): DOI: 10.1007/s12517-016-2309-x

Fouli, H., Al-Turbak, A.S., Bashir, B. and Loni, O.A., 2016. Assessment of a water-harvesting site in Riyadh Region of Kingdom of Saudi Arabia using hydrological analysis. Arabian Journal of Geosciences, 9(5).

Kacimov A.R., Brown, G. 2015. A transient phreatic surface mound, evidenced by a strip of vegetation on an earth dam. Hydrological Sciences J. 60(2): 361-378.

Kacimov A. , Al-Maktoumi. A. and Obnosov, Yu.V. 2022. Seepage through earth dam with clay core and toe drain: the Casagrande-Numerov analytical legacy revisited. ISH J. of Hydraulic Engineering, in press.

Kacimov A.R., Obnosov Yu.V. 2012. Analytical solutions for seepage near material boundaries in dam cores: the Davison-Kalinin problems revisited. Applied Mathematical, 36: 1286–1301

Kacimov A., Yakimov, N.D., Simunek, J., 2020. Phreatic seepage flow through an earth dam with an impeding strip. Computational Geosciences, 24: 17–35.

Luo, Z., Yong, C., Fan, J., Wang, S. and Jin, M., 2020. Precipitation recharges the shallow groundwater of check dams in the loessial hilly and gully region of China. Science of The Total Environment, 742, p.140625.

Missimer T.M, Guo W., Maliva R.G., Rosas J., Jadoon K.Z. (2015) Enhancement of wadi recharge using dams coupled with aquifer storage and recovery wells. Environ Earth Sci 73:7723–7731.

Mohammadzadeh-Habili, J. and Khalili, D., 2020. Assessment of artificial recharge dams and improvement of their groundwater-recharge capacity. Journal of Hydrologic Engineering, 25(5), p.04020011.

Prathapar, S.A. and Bawain, A.A., 2014. Impact of sedimentation on groundwater recharge at Sahalanowt Dam, Salalah, Oman. Water international, 39(3): 381-393.

Reddi, L.N., Ming, X., Hajra, M.G. and Lee, I.M., 2000. Permeability reduction of soil filters due to physical clogging. Journal of Geotechnical and Geoenvironmental Engineering ASCE, 126(3): 236-246.

Ryel R. J., Caldwell M. M., Leffler A. J., Yoder C. K. (2003) Rapid soil moisture recharge to depth by roots in a stand of artemisia tridentate. Ecology, 84(3):757–764

Sato, M. and Kuwano, R., 2015. Suffusion and clogging by one-dimensional seepage tests on cohesive soil. Soils and Foundations, 55(6): 1427-1440.

Sumi, T., Kantoush, S.A. and Saber, M., 2022. Wadi Flash Floods: Challenges and Advanced Approaches for Disaster Risk Reduction. Springer.

Talukdar, P. and Dey, A., 2019. Hydraulic failures of earthen dams and embankments. Innovative Infrastructure Solutions, 4(1): 1-20.

Xanke, J., Salman, A., Al-Karablieh, E., Liesch, T., Salameh, E. and Goldscheider, N., 2020. Hydrogeological site investigation and economic evaluation to assess the potential of managed aquifer recharge in the Lower Jordan Valley. Hydrogeology Journal, 28(2): 745-762.

Yin, Y., Cui, Y., Tang, Y., Liu, D., Lei, M. and Chan, D., 2021. Solid–fluid sequentially coupled simulation of internal erosion of soils due to seepage. Granular Matter, 23(2): 1-14.

Yousif, O.S., Karakouzian, M., Rahim, N.O. and Rashed, K.A., 2017. Physical clogging of uniformly graded porous media under constant flow rates. Transport in Porous Media, 120(3): 643-659.

Zaidi, M., Ahfir, N.D., Alem, A., El Mansouri, B., Wang, H., Taibi, S., Duchemin, B. and Merzouk, A., 2020. Assessment of clogging of managed aquifer recharge in a semi-arid region. Science of The Total Environment, 730, p.139107.
S. A. Prathapar & Abdulla Ali Bawain (2014) Impact of sedimentation on groundwater recharge at Sahalanowt Dam, Salalah, Oman, Water International, 39:3, 381-393, DOI: 10.1080/02508060.2014.895889