Groundwater Recharge in Wadi Channels Downstream of Dams Efficiency and Management Strategies

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Summary

Groundwater recharge dams are used in arid countries to enhance the natural groundwater recharge by a controlled infiltration of stored flood events. The efficiency of this recharge process has been evaluated and the management of the dams has been optimised with regard to a maximum recharge volume.

The study is based on field tests in the Sultanate of Oman and extensive parameters studies with numerical models for different soil types. For the monitoring of the field tests, tensiometers and temperature probes have been installed in the subsoil up to a depth of 20 m. In the numerical models, the flow of liquid water and water vapour has been simulated to observe the wetting as well as the drying process in soil. The recharge percentage has been determined for various boundary conditions.

The results of the parameter studies have been used to develop a method to calculate the recharge efficiency downstream of dams. Additionally, recommendations for the operation of recharge dams are given. A case study and a comparison of the situation without and with a dam show the benefit of groundwater recharge dams.

Background

In arid countries the potential evaporation exceeds the annual rainfall. Thus, the natural water resources are limited and the water shortage has always been one of the restricting factors for the socio-economic development in these regions of the world. At the beginning of the 21st century, most of the arid countries are still developing countries. Considering their increasing growth of population and economy in the near future, the water demand will rise to an unimaginable amount.

Since the availability of surface water varies widely in arid regions, groundwater is often the only reliable source of fresh water. For countries in the Arabian Peninsula, groundwater is the only renewable water resource. Because of the sporadic rainfall, groundwater recharge is limited to the infiltration during the intermittent flood flow in dry wadi channels. Extensive groundwater withdrawal in excess of natural replenishment results in a progressive lowering of the water table in alluvial aquifers and thus a sustainable water supply is endangered or even impossible.

Apart from efforts to limit the water demand, the decreasing groundwater resources can be faced by measures to increase the natural groundwater recharge. Therefore, groundwater recharge dams have been built in many arid countries. Though the storage of rainwater in surface reservoirs by dams has the disadvantage of increased evaporation losses, it brings the advantageous possibility to manage the recharge process by operation of the dam facilities (fig. 1).

fig. 1 Controlled release of stored flood water from a groundwater recharge dam

Objective

The objective of this study is to evaluate the effectiveness of groundwater recharge downstream of dams concerning the amount of recharged water to the aquifer, and to develop management strategies for an optimised operation of the dams. Here, dams in the Sultanate of Oman are exemplary schemes to verify the general approaches.

The two main parts of this work are field tests in the Sultanate of Oman and a parameter study using numerical models. Based on them, the efficiency of the recharge process is evaluated and recommendations for management strategies are given. Thus, suggestions for engineers who are planning and operating recharge dams in arid regions are given.

Field Tests

The field tests have been carried out in co-operation with the Ministry of Regional Municipalities, Environment and Water Resources of the Sultanate of Oman in the Wadi Ahin in the north of Oman. The location has been chosen to represent a typical wadi in this region. To observe the infiltration in a wadi channel under natural conditions, an infiltration basin has been built (fig. 2).

fig. 2 Infiltration test basin during the execution of a test

Underneath the basin, tensiometers and temperature probes have been installed up to 20 m depth. To get to know the functionality of the instruments of the field tests, laboratory tests have been conducted at the Oskar-von-Miller Hydraulic Laboratory of the Technische Universität München.

The evaluation of the temperature measurements shows that the recharge process induces a temperature anomaly into the soil, and that it takes a long period of time until the normal soil temperatures are re-established. Improvements of the recharge monitoring are conceivable because the measurement of soil temperatures is comparatively easy and suitable probes are cheap and robust. Contrary to measurements of the groundwater level, small flood events which do not reach the groundwater table can be detected by measuring the temperature changes in the wetted parts of the unsaturated soil. Since the undisturbed temporal temperature development can be theoretically determined, the occurrence of infiltration events can also be detected retrospectively. By the means of temperature measurements, even weeks or months after a flood event, the infiltration depth can be determined in the top 10 m.

The field tests show that the infiltration rate increases with a rising water level at the surface. By assuming a constant surface discharge, the question arises, whether small channels with a higher water level provide more recharge than wide channels with a low water level. This cannot be answered by the field tests because the width of the wetted surface has been constant due to the geometry of the infiltration basin. To also observe the influence of the flow width on the infiltration, a parameter study with a numerical model has been carried out.

Parameter Study with Numerical Models

The parameter study and a preceding sensitivity analysis of the recharge model are carried out with regard to site-specific and management parameters. The site-specific parameters are summarised by the use of different soil types with characteristic properties. Three soil types have been observed: sandy silt, sand and sandy gravel. The three management parameters are (1) the water level of the surface runoff, (2) the width of the wadi channels, and (3) the duration of the surface wetting (fig. 3).

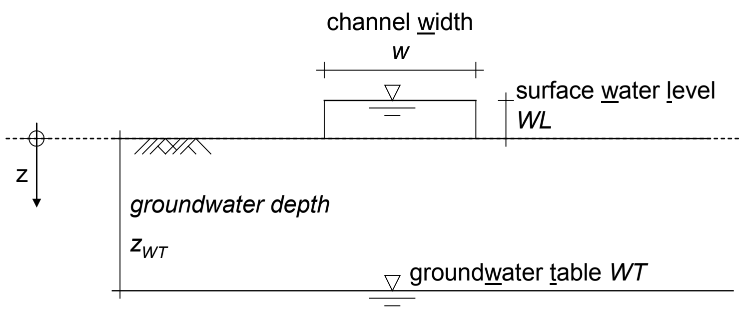

fig. 3 Parameters of groundwater recharge in wadi channels

The parameter study of the recharge process resulted in the following conclusions:

- The most important factor for the infiltration rate is the soil type. To achieve reasonable infiltration rates, at least sand or, even better, a gravel soil should be available.
- The infiltration rate is increasing with an increasing water level of the surface flow.
- The infiltration rate is slightly decreasing with an increasing width of the surface flow, whereas the percolation rate is increasing. Both effects occur due to the influence of the 2-dimensional lateral spreading of the water.
- An increasing groundwater depth reduces the vertical percolation rate.

Results of the Study

Efficiency of Groundwater Recharge Dams

The amount of groundwater recharge can be increased by dams many times over when compared to the natural recharge. This positive effect occurs mainly due to the prevention of flow losses beyond the recharge area, and due to the extension of the infiltration duration. Depending on site-specific boundary conditions and the magnitude of flood events, dams give the possibility to recharge more than 80% of the stored water to the aquifer. Case studies show that recharge percentages of even 95% are achievable. The comparison an exemplary situation with and without dam in fig. 4fig. 4 emphasises the efficiency of groundwater recharge dams.

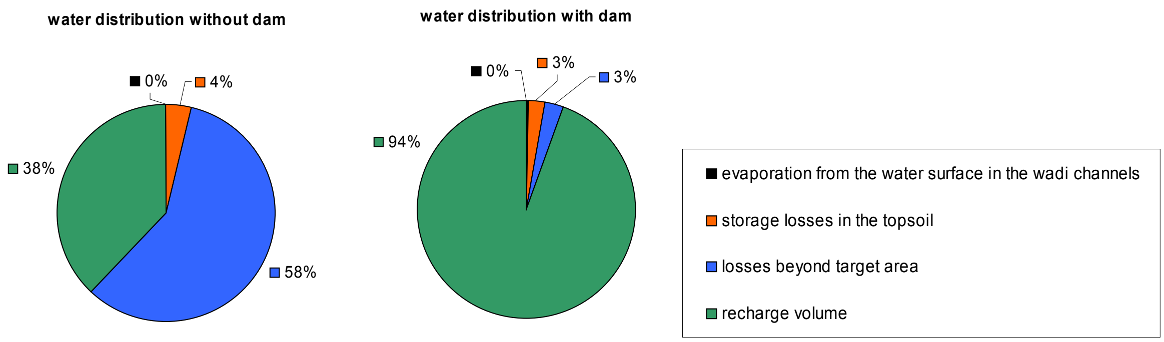

fig. 4 Percentage water distribution without and with dam

In sandy or gravely soils, the infiltration rates are some hundred times higher than the evaporation rates in arid climates. Thus, the evaporation from the water surface in the wadi channels during the recharge events can be neglected. However, after a recharge event, the soil is dried out by evaporation of water vapour. The influence of the evaporation proceeds downwards in the course of time. The zero-flux-plane, which divides the upwards from the downwards flow, progresses downwards at about 0.4 m/year.

As a consequence, the losses in the topsoil above the zero-flux-plane are negligibly small when recharge events occur at least once a year. After long drying periods of several years, the losses amount to some 10% of the stored flood water. These losses can be reduced by an appropriate recharge management; an examples shows that they may be below 3% even after five years of drying.

Management Strategies for Groundwater Recharge Dams

The objective of an optimised recharge management is to spread stored water – spatially and temporally – to the best benefit for the aquifer (fig. 5). The basic principles to achieve this are:

- The culvert discharge of the dam should be as low as possible; a minimal discharge should maintain an emptying time of the reservoir of ten to fifteen days.
- Flow losses beyond the target area of recharge should be avoided by activating enough recharge channels to keep the runoff within this area.

Apart from this basic rule, namely, to infiltrate as long as possible in a wetted area that should be as small as possible, the used wadi channels should be selected according to the permeability of the subsoil.

fig. 5 Controlled recharge flow in a wadi channel

Although it is simple, it is the most important principle: The higher the permeability of the subsoil, the higher the recharge efficiency. Low infiltration rates due to the properties of the in-situ soil cannot be compensated even by the best management. For this reason, a high permeability of the used recharge channels should be maintained during the design (site selection) and the operation (channel activation) of a dam as well as by the maintenance of the recharge channels (periodical removal of clogging layers).