Electronic Supplementary Material - Hydrogeology Journal

Sixty years of global progress in managed aquifer recharge

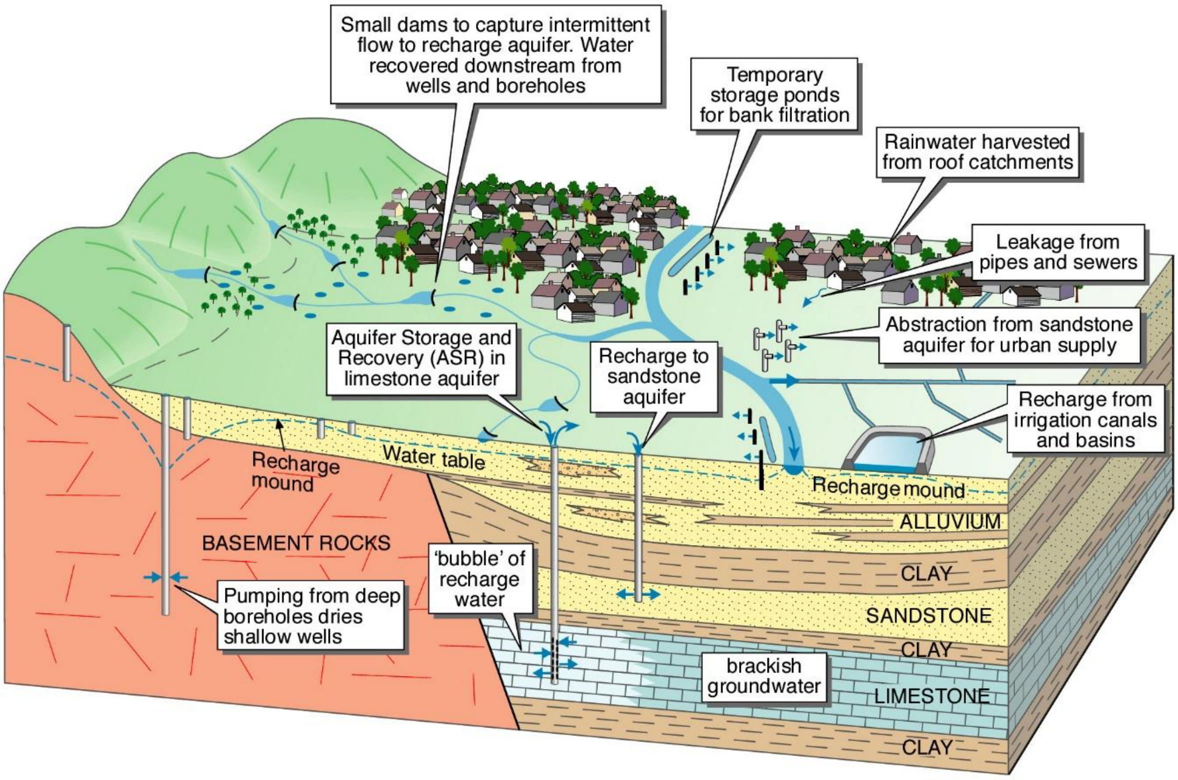
Dillon, P., Stuyfzand, P., Grischek, T., Lluria, M., Pyne, R.D.G., Jain, R.C., Bear, J., Schwarz, J., Wang, W., Fernandez, E., Stefan, C., Pettenati, M., van der Gun, J., Sprenger, C., Massmann, G., Scanlon, B.R., Xanke, J., Jokela, P., Zheng, Y., Rossetto, R., Shamrukh, M., Pavelic, P., Murray, E., Ross, A., Bonilla Valverde, J.P., Palma Nava, A., Ansems, N., Posavec, K., Ha, K., Martin, R. and Sapiano, M. [* pdillon500@gmail.com]

ESM2: Photographs of managed aquifer recharge projects

This photograph gallery was collated especially for the journal paper by members of a Working Group on 60 years history of MAR of the IAH Commission on Managing Aquifer Recharge. Captions contain brief descriptions of the projects and these are intended to be a useful educational resource to illustrate the variety of methods used for MAR, for a range of purposes, water types and end uses.

This is in addition to ESM1, which is an anthology of national histories on MAR.

ESM2 Contents:



Managed aquifer recharge is adapted to the local hydrology and hydrogeology, and is usually governed by the type of aquifer, topography, land use, ambient groundwater quality and intended uses of the recovered water. This diagram shows a variety of recharge methods and water sources making use of several different aquifers for storage and treatment with recovery for a variety of uses. An understanding of the hydrogeology of the locale is fundamental to determining options available and the technical feasibility of MAR projects. Recharge shown here occurs via streambed structures, river bank filtration, infiltration basins and recharge wells. (*Adapted from Gale, 2005, with permission in Dillon et al 2009*)

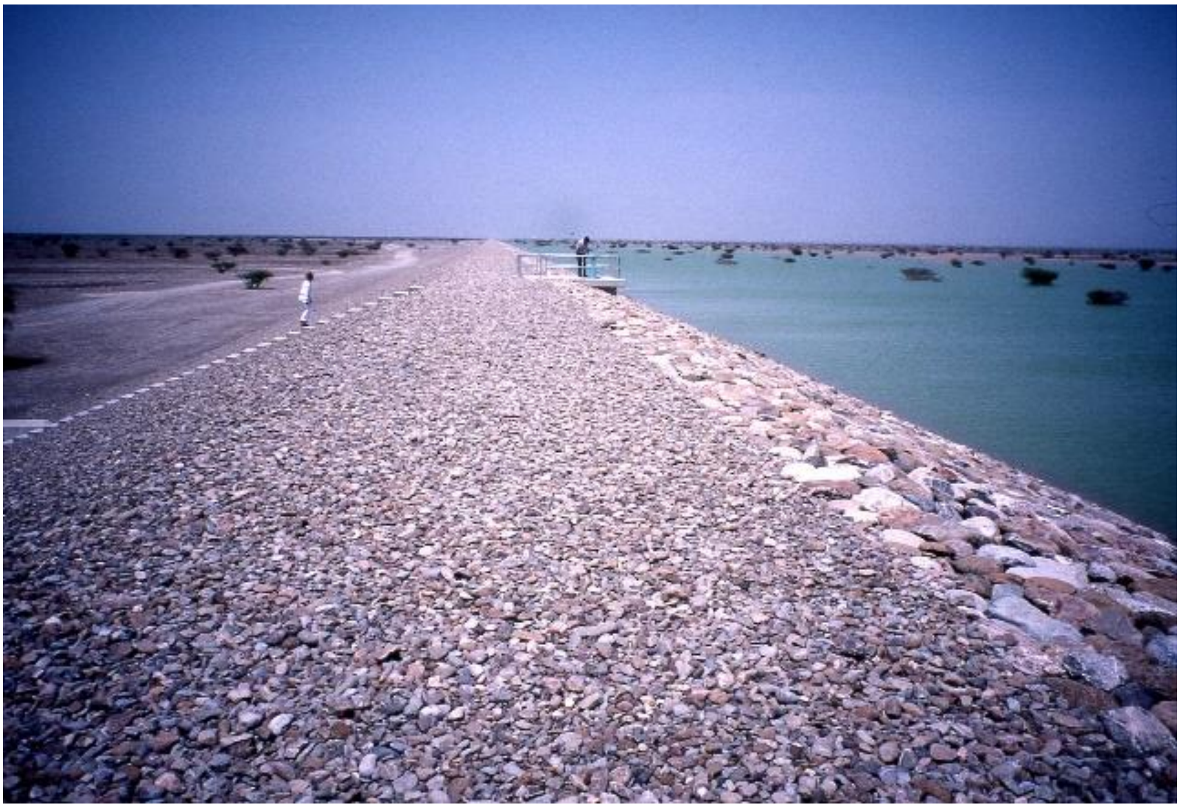
Dillon, P., Pavelic, P., Page, D., Beringen H. and Ward J. (2009). Managed Aquifer Recharge: An Introduction. Waterlines Report No 13, Feb 2009. 65p. https://recharge.iah.org/files/2016/11/MAR_Intro-Waterlines-2009.pdf (accessed 8 Jun 2018)

Gale, I.N. (2005). Strategies for managed aquifer recharge in semi-arid areas. UNESCO-IHP Publication. https://recharge.iah.org/files/2017/01/Gale-Strategies-for-MAR-in-semiarid-areas.pdf (accessed 12 Mar 2018)

Streambed channel modifications

Photo 1.1 Percolation tank construction near Baramati, Maharashtra, India, in the 1970s with women carrying murum and clay one bowl at a time to patiently construct the designed embankment. (*Photo from Agricultural Trust Baramati*).

Sand dams in the Burdekin River, Queensland, Australia, to spread water and increase recharge to aquifers used for irrigation supplies. Recharge channels and pits are also used in this area. About 40 Mm^3 has been recharged annually since the 1970s. (*Photo courtesy of Keith Bristow, CSIRO*).



Ahin recharge dam on the Batinah Plain, Oman, constructed in 1994, is a large dam (crest length 5640 m, crest height 8 m) with a detention capacity of 6.8 Mm^3. This is one of the 43 recharge dams, with an aggregated capacity of 95 Mm^3 constructed in Oman during the period 1985-2011 (Oman, MRMWR, 2012). Their purpose is to enhance aquifer recharge primarily to support irrigation; and also to protect the villages and agricultural land in the coastal zone against (previously) devastating flash floods. The dams intercept floods from a catchment with a mean annual rainfall less than 140 mm and potential evaporation around 2000 mm/yr. The detained water is released in a controlled way to recharge the aquifer zone downstream *(Photo: Jac van der Gun, 1995).*

Oman, MRMWR (2012). Dams in Oman. Ministry of Regional Municipalities and Water Resources. https://issuu.com/kabirahmed07/docs/dams_in_oman (accessed 24 July 2018)

Bank filtration

River bank filtration monitoring cross-section at the River Elbe at Torgau, Germany. Since 1981, Torgau waterworks abstracts up to 150,000 m^3/day from 42 wells located along a 15 km-long river stretch. The wells are located at mean distance of 300 m from the river bank. The travel times of the bank filtrate range from 50 to >200 days resulting in an effective removal of organic trace compounds. A monitoring cross-section with observation wells between the river and the abstraction wells allows sampling below the river bed (buried membrane pumps) and from different depths of the 55 m-thick sand and gravel aquifer. (*Photograph courtesy of T. Grischek, HTWD*)

Drilling of river bank filtration wells at the River Nile, Luxor, Egypt, March 2018. Seasonal low river water level, frequent spills of oil and other pollutants and high turbidity during high flow cause problems in surface water abstraction and subsequent treatment. A short distance between the abstraction wells and the river bank is sufficient to remove particles, to buffer spills and to ensure a high portion of bank filtrate and a low portion of manganese-rich land-side groundwater. (*Photograph courtesy of T. Grischek, HTWD*)

First flood-proof river bank filtration well in Srinagar, Uttarakhand, India. After a severe flood in 2013, a concept to construct flood-proof wells has been developed (NIRWINDU project) and realized in 2017 to protect city drinking water supplies. (*Photo courtesy of F. Musche, HTWD*)

Water spreading

Percolation ponds Nahaley Menashe, Israel. Since the 1960s, flash flood waters of four wadis south of Mount Carmel have been diverted to recharge the coastal plain aquifer in the dune area, which is now adjacent to the Hadera Desalination Plant (seen in background). The average annual yield of flood water is 10–15 Mm^3. The project consists of diversion structures, conveyance channels, a settling basin with an area of 51 ha to remove sediments and three percolation basins with a total area of 48 ha. Thirty seven pumping wells that are connected to the national water supply grid encircle the recharge area. The percolation ponds are now used also to store the desalination plants excess product water outside of the flood season. (*Photo by Dr. Joseph Guttman, Mekorot water company*)

At San Luis Rıo Colorado, Sonora, Mexico, oxidation lagoons (at a wastewater treatment plant in the background) have annually discharged 8.2 Mm^3 treated water to intermittent infiltration basins in the middle distance for more than 10 years. In the foreground, some water is starting to be used to establish constructed wetlands. *(Photo, April 2018, courtesy of Hernández Humberto, Organismo Operador Municipal de Agua Potable, Alcantarillado y Saneamiento de San Luis Rıo Colorado, Sonora, Mexico).*

In Arizona, USA, the Granite Reef Underground Storage Project (GRUSP) takes surface water from the South Canal of the Central Arizona Project through a delivery canal to infiltration basins to recharge the unconfined aquifer that supplies the City of Phoenix. The facility, except for the source water canal, is totally constructed in the Salt River bed. It has been operating since 1994 and is permitted to recharge up to 115Mm^3/yr through 7 basins. (*Photo courtesy of Mario Lluria, HydroSystems Inc.*)

Basin infiltration Jäniksenlinna MAR plant, Tuusula, Finland. During winter, ice cover is formed on the basin surface, but this does not prevent infiltration. Jäniksenlinna MAR plant is used for potable water production: humic lake water is infiltrated, it travels 400–650 m in the ground with a detention time of 30–60 days. During that time, humic substances are biodegraded and/or removed by adsorption. This operation started in 1979 and comprises both basin and well infiltration with total capacity of 13,200 m^3/d. Cascade aeration helps sustain aerobic conditions that are important for aerobic biodegradation of humic substances in the soil. (*Photograph by Unto Tanttu*)

In Santiuste Basin, Segovia, Spain, water is diverted from Voltoya River MAR by a dam and 10 km of 1200-mm diameter pipe and discharges as shown to an infiltration pond that overflows into 27 km of MAR infiltration canals. The system was established in 2002 and designed for a maximum flow-rate of 100 l/s and to deliver up to 8.5 Mm^3 in each 6-month winter-spring cycle, whenever the Coca Gauge station registers over 1,200 l/s in the Voltoya River. The infiltration pond has an area of 1.4 ha, and the two canals an area of 6.1 ha. The purpose is to increase water availability for irrigation and now 28% of water used for irrigation is derived from MAR. A small amount is used for the regeneration of wet-lands (La Iglesia salt-lake). Santiuste village wastewater treatment plant water is also discharged into the MAR canal for recharge. Three artificial wet-lands have also been built to improve the purification process. Between 2002 and 2015 the total volume infiltrated was 34 Mm^3. The mean groundwater level has raised 1.47 m, resulting in 30% energy savings to pump water with respect to the previous cost. (*Photo: Enrique Fernández Escalante, March 2017.*)

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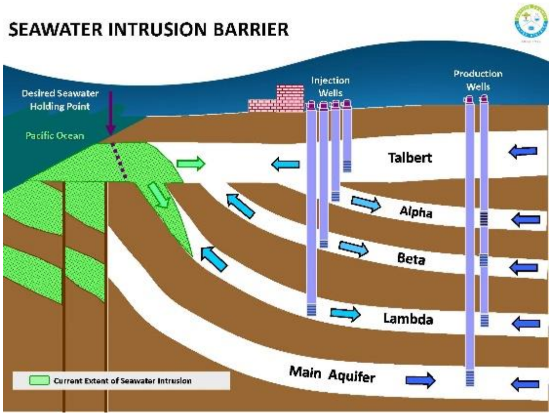
In Italy, the Suvereto infiltration basin uses flood-water and it was designed and set in operation in 2018, applying the newly issued Italian regulation on artificial recharge of aquifers (DM 100/2016). The infiltration basin is located at a pre-existing topographical low near the Cornia River in a groundwater recharge area where the aquifer is composed of gravel and sand. The river, having intermittent flow, provides recharge water during high flow periods, including floods, and when discharge is above the minimum ecological flow. The facility consists of the following elements: i) intake work on the River Cornia; ii) the inlet structure control system, managed by quality (mass spectrometer defining surface water spectral signature) and level probes, and allowing pumping into the facility at predefined head and chemical quality thresholds; iii) a sedimentation basin; iv) the infiltration area (less than 1 ha area); v) the operational monitoring system, based on a network of piezometers where both continuous data (head, temperature, electrical conductivity and dissolved oxygen) are gathered and discrete measurements/sampling performed. Depending on the climatic conditions, it is estimated that the volume of diverted surface water may vary between 0.3 and 2 Mm^3/yr. *(Photos: Rudy Rossetto)*

Recharge wells

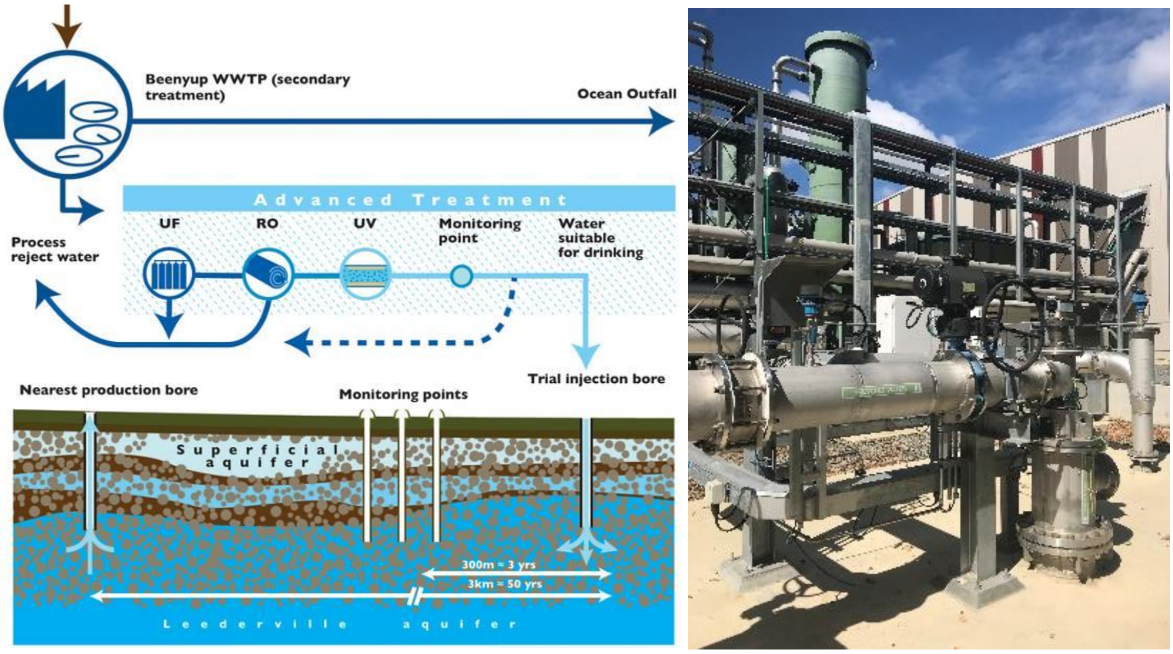
At Cocoa, Florida, USA, ten aquifer storage and recovery wells, including one in the foreground, store and recover treated drinking water using the underlying aquifer at a depth of 100 to 130 m. The volume stored below ground during the low demand period and recovered in the high demand period at Cocoa is ten times the volume of the two storage tanks behind. The unit storage cost of ASR was less than 2 per cent of the alternative cost of constructing additional tanks. (Dillon *et al* 2009; see reference details above). The system commenced operation in 1987 and has the capacity to recharge and recover 45,000 m^3/d (Pyne 2005) (*Photo: Peter Dillon*)

Pyne, R.D.G. (2005). Aquifer Storage Recovery: A Guide to Groundwater Recharge Through Wells. ASR Systems, 2nd Edition, 608p.



Orange County's Groundwater Replenishment System (GWRS) in California, USA, is the world's largest water purification system for indirect potable reuse. This takes highly treated wastewater that would otherwise be discharged into the Pacific Ocean, and further treats it with microfiltration, reverse osmosis and ultraviolet light with hydrogen peroxide. The high-quality water that is produced meets all USA drinking water standards. The water indirectly, via aquifers, supplies 850,000 residents in an area with an annual rainfall of 360 mm. GWRS started in 2008, but was an expansion of the 'Water Factory' that began in the 1970s. It currently produces 0.37 Mm^3/day and will grow to 0.49 Mm^3/day by 2023. The water is injected via 23 multi-port wells into a series of coastal aquifers to prevent saline intrusion occurring as a result of groundwater exploitation. The water is also fed with water from other sources into a large number of infiltration basins. GWRS protects and improves groundwater quality and enables continuing use of the groundwater system for vital water supplies. (*Figures courtesy of Orange County Water District*)

The Paddocks constructed wetland and urban stormwater harvesting system was developed by the City of Salisbury, South Australia, and commenced operation in 1996. The scheme was conceived to mitigate flooding, to improve stormwater quality, to provide urban recreational amenity and wildlife habitat, and also to harvest water in winter for summer irrigation. On average 60,000 m^3/yr is harvested from an 80-ha urban-residential catchment and recharged (Kretschmer 2017). When water quality is suitable, stormwater is injected into a confined limestone aquifer with native groundwater salinity of 1800 mg/L, via a 164-m deep aquifer storage and recovery (ASR) well with open-hole completion. Although native groundwater salinity was too high for irrigation, ASR allows a volume of about 80% of the volume of fresh water recharged to be recovered for sustainable irrigation of parks and sporting grounds in summer via a distribution system that extends through the City of Salisbury and connects a number of stormwater ASR systems. (*Photos by Peter Dillon*)



Perth Groundwater Replenishment Project, Western Australia, which commenced operations in 2017 at 14 Mm^3/yr using advanced treated recycled water to recharge a confined aquifer that is an important contributor to Perth's drinking water supply. It will double its annual recharge by 2019 when a treatment plant and a total of 4 wells will store water in the Leederville and Yarragadee aquifers. The project will prevent saline intrusion and allow expansion of use of the groundwater system to meet water supplies in an area experiencing a drying climate, where surface water supplies have reduced over the last 40 years and the population has steadily increased *(Photo and diagram courtesy of Water Corporation, Western Australia).*