Recharge

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Contents

What is recharge?

Recharge is the replenishment of groundwater in aquifers by rainfall. Recharge can be direct - rainfall infiltrates directly into aquifers through soil, sediments or rock; or it can be indirect - surface water flows first over impermeable land and into rivers before later infiltrating down into aquifers in a different place from where it fell as rain. Recharge is one of the main controls on groundwater resources.

Recharge estimation techniques in Africa

Groundwater recharge is one of the most difficult parameters to measure in the assessment of groundwater resources, but it is vital for reliable projections of sustainable resource development.

There have been many studies of groundwater recharge across Africa. These vary significantly in terms of the study scale; the geographical, climatic and geological characteristics of the region of interest; the quality of data used; and the estimation methods applied. The following review was written for the UPGro project Groundwater recharge in Africa: identifying critical thresholds, which finished in 2014. The project reviewed more than 200 recharge studies in Africa, examining relationships between rainfall and recharge, and evidence for thresholds controlling recharge. Key findings were:

- the importance of using multiple methods to estimate recharge

- the importance of reporting recharge as decadal, rather than annual averages, because of the high year-to-year variability in recharge, particularly in semi-arid and arid regions

- while broad relationships exist between average rainfall and recharge, such relationships become nonlinear when long-term average annual rainfall is less than 500 mm. Rainfall intensity and land cover are also important controls on recharge. In future, climate change is expected to lead to increased rainfall intensity, and so a better understanding of the role of episodic high intensity rainfall events in governing recharge will become increasingly important.

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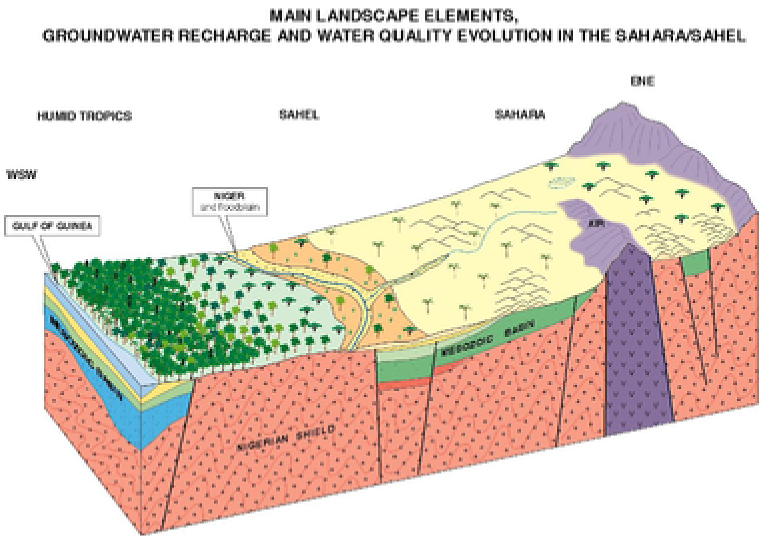
Introduction

The major limiting factor in the sustainable use and management of Africa's water resources is whether the stored groundwater is renewable or non-renewable. Numerous studies have shown that in arid and many semi-arid areas the large bodies of fresh and useable groundwater reserves are non-renewable i.e. palaeowater recharged under wetter climates of the early Holocene or late Pleistocene, prior to the onset of a more arid climate around 4500 years BP (Edmunds et al., 2004).

The purpose of this review is to examine the methods for estimating active, renewable recharge in the African context according the contrasting geology and hydrogeological contexts as well as the range in present-day hydroclimatic conditions. Techniques for characterising the non-renewable components are well documented. This review will focus on low-rainfall areas which depend critically on the renewable shallow groundwater. Many higher-rainfall areas also depend on groundwater for a safe source of water but the quantities are mostly reliable except in areas with seasonal (monsoonal) rains during prolonged dry seasons. A range of techniques are available which attempt to quantify modern recharge and rates can vary widely according to rock type and landscape. Several useful reviews are available, some of which are relevant to Africa (Simmers et al., 1988; Scanlon, Healy and Cook, 2002; Xu and Beekman, 2003; Scanlon et al., 2006). This review is selective and focuses on those methods which are most widely used, likely to have wide and practical application, and can be applied or adapted to local rather than regional scales over the African continent.



Main landscape elements and recharge environments of northern Africa typified by a section from Central Sahara to the Guinea

The geology of Africa presents several types of terrain that can be considered as major units for groundwater recharge. Several large sedimentary basins store groundwater predominantly as palaeowater, especially in North Africa (Sahara/Sahel) but also in southern Africa and in its coastal margins. In many of these areas the water table is deep and modern replenishment not an issue, but in basin margins the shallow water tables may receive modern recharge. Most sedimentary aquifers contain clastic sediments (limestones are rare except coastal margins); where sandstones dominate, recharge may be significant even with moderate or low rainfall. Secondly, large areas of Africa are covered by permeable sands of Quaternary age; these deposits, e.g. dune fields from former arid climates, may extend into wetter areas such as the Gulf areas of West Africa. Volcanic rocks, found mainly in the East African rift valley, have significant resources of renewable groundwater. Large areas of ancient igneous and metamorphic rocks form the basement and these rocks, traditionally considered as low permeability, are likely to give rise to the most important aquifer series per capita. The likelihood of modern recharge to groundwater in basement fracture systems and the regolith is a main challenge and topic of this review.

The interface between modern water and palaeowater

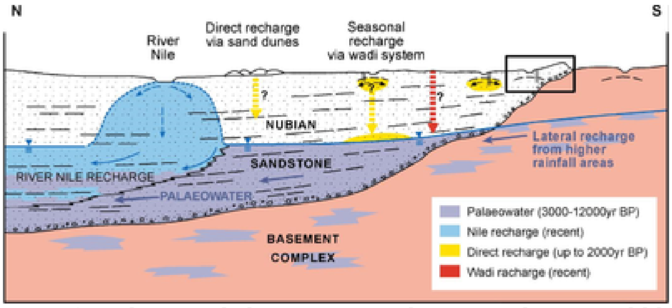
Geology and climate create constraints on groundwater recharge. Controls on both diffuse rainfall recharge and to focused recharge via wadis or depressions need to be considered, which may be influenced by terrain (slope) as well as soils and bedrock geology. Vegetation cover and its variation with time is an important variable, and the impact of rapid land-use change (e.g. clearance of trees and scrub) may increase recharge rates considerably. It is also possible that, if salinity in dryland areas increases as a result of changes in vegetation, this can cause water stored for millennia in the unsaturated zone to infiltrate down to the water table (Allison et al.1990). It is very important therefore that recharge assessment is based in advance upon a reconnaissance of the best available knowledge of landscape, geological and environmental evidence.

Shallow groundwater (<30 m) is most valuable for rural development and most productive wells are to be found within this limit in both hard and soft rock terrain. Construction by manual work or mobile drilling rigs is straightforward within this 30 m range. Where communities rely on such wells at the present day this may be a first sign that renewable groundwater exists. Across much of the semi-arid regions of Africa the balance between renewable and non-resources is critical. Chemical and isotopic tracer studies have been shown as the best way to demonstrate their presence especially in the widely distributed clastic sedimentary aquifers. The case study from Abu Delaig Sudan (see inset) indicates that zero diffuse recharge takes place through the unsaturated zone, yet focused recharge from wadis is an important renewable resource and that palaeowaters at depth are non-renewable under present-day climates. This emphasises the need to understand the relationships between water movement in both the unsaturated and saturated zones.

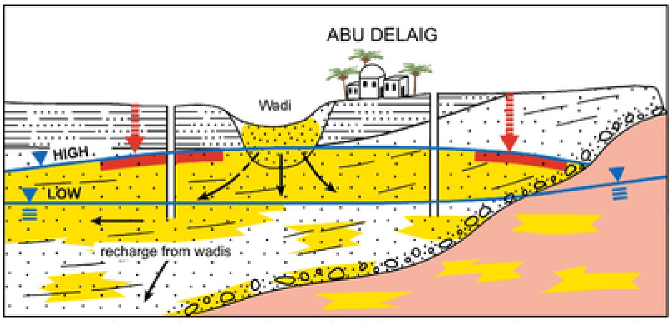
The regolith presents many challenges for recharge and resource estimation.[should we include a modified Acworth diagram?]. It is characteristically heterogeneous with layering and/or lenses of permeable sandy material and interbedded clays, typically overlying permeable material overlying the basement rock; the depth to the latter (0 to 30 m typical) is variable depending on many geological factors (not discussed here). Surface deposits are frequently sandy and permeable but recharge may be hindered by clay lenses. Drilling may also intercept groundwater lenses which are not in hydraulic continuity with the main aquifer.

Case study of Abu Delaig and the Nile Valley

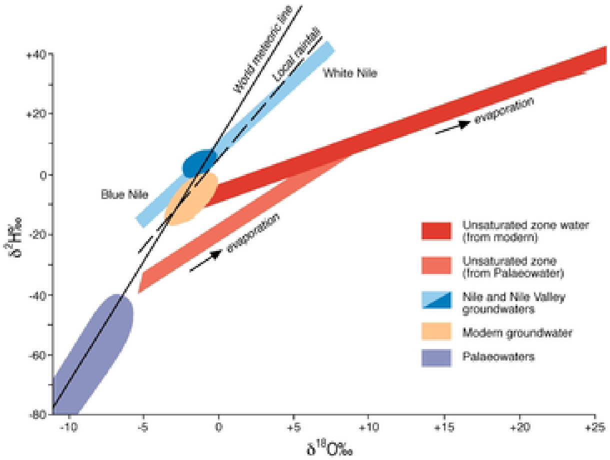
Wadi Hawad with its minor tributaries lies in the Butana region of Sudan between the Nile and the Atbara Rivers, underlain by an embayment of the Nubian Sandstone Series (Cretaceous) which in turn overlies the Basement complex. The interfluve areas are flat grassland with sandy soil but often with a clay matrix which imparts a relatively impermeable surface. Much of the area is grazed by local or nomadic farmers who rely not only on the shallow groundwater resource exploited by hand dug wells (to 26 m) but also on several deep (to 150 m) pumped boreholes drilled in the Nubian sandstone.

- 

Schematic cross section of Wadi Hawad showing groundwater recharge and likely water resources

- 

Schematic cross section near town of Abu Delaig, with negligible direct recharge via the predominantly clay surface of the interfluve, as shown by chloride profiles. Recharge through wadi beds extends laterally beneath interfluves, as indicated by tritium. It is uncertain to what extent water from these 'freshwater lenses' recharges the deeper aquifer



Summary diagram of all isotopic data from the Wadi Hawai area - rainwater; River Nile; and shallow & deep groundwater, including moisture in the unsaturated zone

Measuring groundwater recharge

Estimating recharge requires a conceptual understanding of the processes that link rainfall to the saturated aquifer. This can be done through two main methods - physically though measurement of water table fluctuations in response to rainfall, or chemically using environmental tracers, where inert rainfall indicators can be tracked via the unsaturated zone or in the groundwater body itself. In Africa both approaches have been used and conjunctive use can be informative although it is often difficult to combine methods for logistical reasons. The main limitations are instrumental, restricting the use of physical measurements of seasonal water levels as well as knowledge of aquifer properties. Similarly some tracer methods are expensive. However the results of research studies involving careful long-term measurement or multiple tracers combined with improved hydrogeological knowledge can be extrapolated to give guidance for more general field application. While it is possible to estimate recharge locally, problems remain in determining the spatial variability of recharge.

Measurements of rainfall flux through the unsaturated zone are widely used for recharge estimation. However physical techniques developed mainly for soil-water studies in an agricultural context are rarely suitable for estimating groundwater recharge. For recharge studies, moisture must pass below a certain depth (often termed the zero-flux plane) where only downward movement takes place. In homogeneous porous sediments, near steady-state movement (piston flow) takes place towards the water table. It is important that measurements of diffuse groundwater recharge only consider data below the zero-flux plane.

In heterogeneous sediments in (semi-)arid terrain, by-pass (macropore or preferential) flow may also be an important process. In older sedimentary formations joints and fractures are naturally present. In some otherwise sandy terrain where carbonate material is present, wetting and drying episodes may lead to mineralisation in and beneath the soil zone, as mineral saturation (especially calcite) is repeatedly exceeded. This is strictly a feature of the zone of fluctuation above the zero-flux plane, however, where calcretes and other near-surface deposits may give rise to hardgrounds with dual porosities. Below a certain depth the pathways of soil macropore movement commonly converge and a more or less homogeneous percolation may be re-established. In some areas, by-pass flow via macropores is found to be significant as in areas of Botswana. Preferential flow may account for at least 50% of fluxes through the unsaturated zone (Beekman et al., 1999; De Vries et al., 2000) and this is verified for example by the presence of tritium at the water table (Beekman et al., 1997).

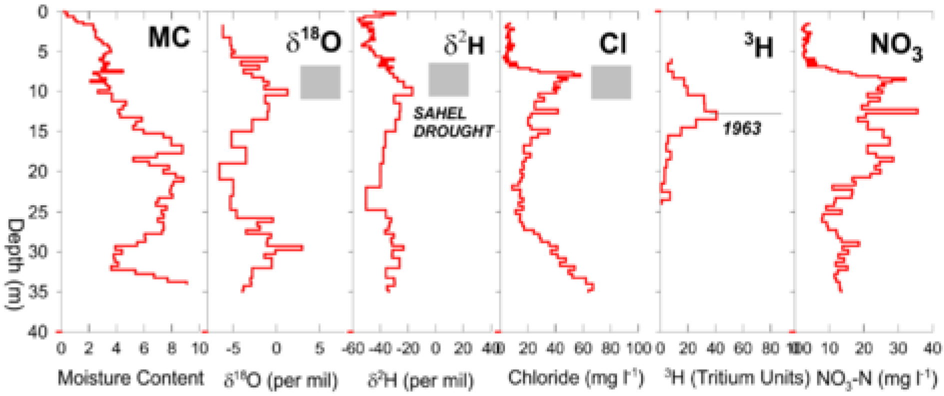
Radioactive isotope tracers: Tritium and ^{36}Cl

Tritium has been widely used in the late 20th century to advance our knowledge of hydrological processes, especially in temperate regions (Zimmerman et al., 1967). It has also been used in a few key studies in (semi-)arid zones to measure recharge rates. In several parts of the world including the Middle East (Edmunds and Walton, 1980; Edmunds et al., 1988), North Africa (Aranyossy and Gaye, 1992; Gaye and Edmunds, 1996) and Australia (Allison and Hughes, 1978), classical profiles from the unsaturated zone show well-defined 1960s tritium peaks some metres below surface, indicating homogeneous movement (piston flow) of water through profiles at relatively low moisture contents (2–4 wt%). These demonstrate that low, but continuous rates of recharge occur in many porous sediments. In some areas dominated by indurated surface layers, deep vegetation or very low rates of recharge, the tritium peak is less well defined (Phillips, 1994), indicating some moisture recycling to greater depths (up to 10 m), although overall penetration of modern water can still be estimated. The usefulness of tritium as a tracer has now largely expired due to radioactive decay (half-life 12.3 years). Nevertheless the evidence and experience from studies in the late 20th century still convey an important lesson.

^{36}Cl (half-life 301,000 years), which also was produced during weapons testing, still offers ways of investigating unsaturated zone processes and recharge although only at a non-routine level. However, in studies where both ^{3}H and ^{36}Cl have been applied, there is sometimes a discrepancy between recharge indications from the two tracers due to the non-conservative behaviour of tritium (Cook et al., 1994; Phillips, 1999). Nevertheless, the position and shape of the tritium peak in unsaturated zone moisture profiles provides convincing evidence of the extent to which 'piston displacement' occurs during recharge, as well as providing reliable estimates of the recharge rate.

Stable isotopes

Stable isotopes have been used in the study of recharge but in general only semiquantitative recharge estimates can be obtained. At high rainfall, infiltration undergoes seasonal fractionation within the zone of fluctuation (Darling and Bath, 1988), but this seasonal signal is smoothed out and little variation remains below the top few metres (zero flux plane). In (semi-) arid zones, however, where low recharge rates occur, the record of a sequence of drier years may be recorded as a pulse of 18O-enriched water, as recorded for example from Senegal (Gaye and Edmunds, 1996). This case study (see figure below) illustrates the value of the stable isotope evidence in validating the evidence of other tracers (tritium and chloride) Extreme isotopic enrichment in the unsaturated zone accompanies chloride accumulation over intervals when recharge rates are zero (Darling et al., 1987) and as illustrated below.



Profiles of tritium, stable isotopes, chloride and nitrate in the unsaturated zone from the same location - profile L18, Louga, Senegal. This profile records the impact of the Sahel drought from 1969 to 1989

Chloride – diffuse recharge measurement

Numerous examples of the application of Cl as a conservative tracer in recharge calculations have been published, and Cl mass-balance methods probably offer the most reliable approach to recharge estimation for low rainfall semi-arid and arid regions (Allison et al. 1994; Scanlon et al. 2006 more). Chloride analysis is inexpensive and is widely applicable, bringing it within the budgets of most recharge investigations, although the capacity for accurate measurements of Cl at low concentrations is required. The most common method is the recovery of profiles from unconsolidated sands to provide long-term estimates of recharge at a point source.

The methods of field investigation are straightforward and involve the recovery of samples by dry drilling methods. Techniques used in Africa include augur (up to 45 m), percussion drilling, or by taking samples (up to 70 m) from side walls of dug wells (Bromley et al.). Samples are immediately sealed in glass jars or polythene bags to avoid moisture loss. Moisture content is measured and chloride extracted by elutriation using demineralised water and then analysed, typically by ion chromatography, calculating pore water concentrations according to the dilution.

A number of criteria must be satisfied or taken into account for successful application:

1. surface runoff is minimal
2. Cl is solely derived from rainfall
3. Cl is conservative with no additions from within the aquifer
4. steady-state conditions operate across the unsaturated interval where the method is applied (Edmunds et al. 1988, Herczeg and Edmunds 1999, Wood 1999).

As with tritium, it is important that sampling is made over a depth interval which passes through the zone of fluctuation.

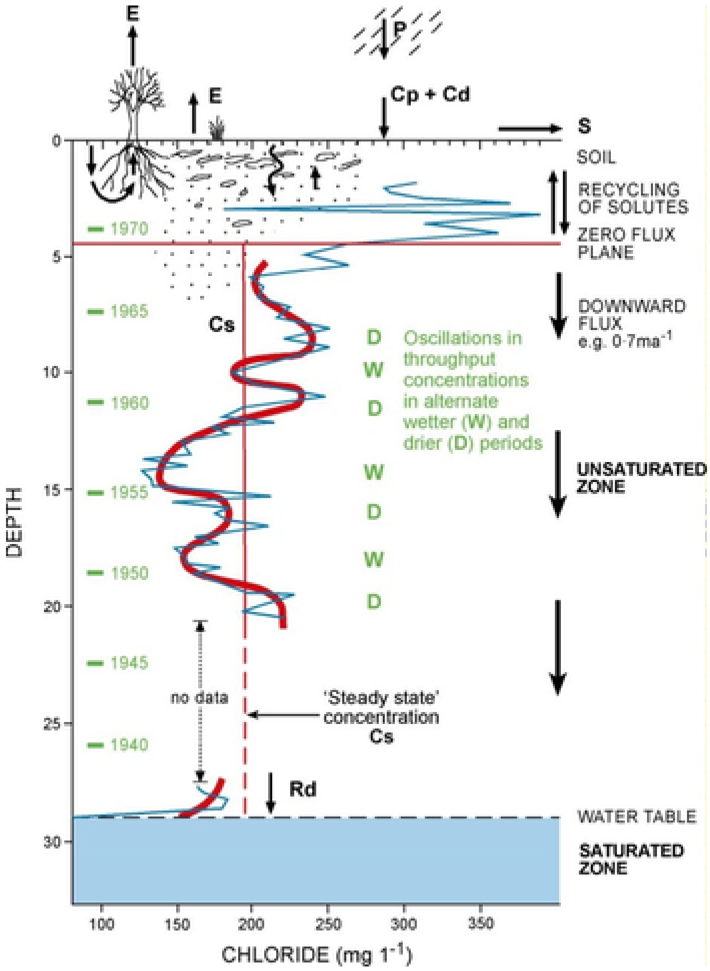
The mean direct recharge rate under steady state conditions is given by the following equation, assuming surface runoff (S) is negligible:

$R= C_P P/C_R – S$

where:

C_R is the mean chloride concentration of moisture below the root zone C_P is the weighted mean chloride in total deposition P is the mean annual rainfall S is the surface runoff

An illustrated example of a chloride mass-balance recharge estimation from a study in Akrotiri, Cyprus is given in the figure below. The sample site was on Quaternary coastal sand dunes with scrub vegetation and mean annual rainfall (P) of 420 mm. Bulked samples were taken every 0.5 m to the water table (except where shown) at 28 m (in later studies samples were taken at 0.25 m using hand augur). Profile shows typical chloride enrichment in the upper 4 m where recycling takes place above the zero flux plane (ZFP). (Some mineralisation may also take place in this zone locking up Cl in closed pore spaces which are then accessed by the destructive sampling technique used.) Below the ZFP a steady-state profile is found with a mean Cl concentration of 200 mg/l. Using the above formula a long term average recharge of about 50 mm/a was derived (Kitching et al., 1980). In this example, oscillations in the Cl correspond with climatic variations and match well the drier and wetter intervals in the second half of the 20th century. A downward moisture flux was estimated at 0.7 m/a. The chemical composition of the groundwater at the water table is comparable to that in the unsaturated zone, suggesting this route is the main source of recharge to the aquifer.



Chloride mass-balance methods for groundwater from the saturated zone

The chloride mass-balance (CMB) approach was originally applied to estimate recharge rates in the saturated zone (Eriksson and Khunakasem, 1969), but there has been less published on this compared with unsaturated zone applications.

A simple application is the study of northern Senegal where the recharge estimates with Cl samples from shallow groundwater (taken from dug wells across a wide area) compare closely with unsaturated zone profiles from the same area, pointing to a homogeneous relationship between the rainfall recharge and the groundwater resource.

In areas where the hydrogeology is heterogeneous with both focused and diffuse recharge components the estimation of recharge using CMB techniques is more complex, and both physical and chemical (tracer) data are required. However if a mass-balance approach is adopted the shallow groundwater chemistry (an integrated record of first arrival of groundwater by mixed pathways) can still provide information on recharge. This is based on the same assumptions (above) as for diffuse recharge. A good conceptual model of the hydrogeology is essential and conjunctive use of physical and chemical approaches is desirable.

A recent example of application of the chloride mass balance to an area of basement in Zimbabwe, the Romwe catchment, is given by MacDonald and Edmunds (2013) where it could be validated with estimates of recharge made using physical methods. Groundwater chemistry (mainly major ion ratios) was used to investigate the relative recharge rates in light and dark bands in the gneiss and to test whether soil type was a good indicator of the underlying geology. The CMB method tested in a control catchment was then used to upscale recharge assessment in a larger area. Over and above the limitations made for the unsaturated zone, the effective rainfall must be measured requiring flow data for the catchment. Some limited agricultural return also needed to be taken into account. Groundwater recharge of 21 mm was derived for the mafic aquifer comparing well with the estimates of 24 mm, made separately, using moisture balance and water table fluctuation methods, respectively. The recharge of 4.4 mm calculated for the felsic aquifer does not compare as well with the corresponding 14 mm using the water table fluctuation method. , However, it supports recharge being higher in the more highly weathered mafic igneous rocks of the basement aquifer and this has a wider significance for resources estimation.

Physical techniques

The **water balance** approach is a useful physical technique for estimating groundwater recharge. This approach forms the basis for many catchment and groundwater models. In essence, the technique involves accounting for all the water entering or leaving and aquifer. The equation can be written as:

$R = P + Q_{on} - Q_{off} - ET - \Delta S - Q_{abst}$

where:

R is recharge

P is precipitation

Q_{on} is runon

Q_{off} is runoff

Q_{abst} is groundwater abstraction

ET is evapotranspiration

ΔS is change in storage

Each component must be expressed in the same units (e.g. mm/day or m/year). For an aquifer, the terms on the right hand side of the water budget equation are generally measured or estimated, and recharge is calculated as the residual. The disadvantage of the water balance approach is that uncertainties in each of the terms are propagated into the recharge estimate. The approach is also used to estimate recharge using physical lysimeter experiments. Lysimeters are containers filled with soil (disturbed or undisturbed) that are hydrologically isolated from the surrounding soil and used to measure components of the water balance. The inputs and outputs of lysimeter experiments are highly controlled and the method is much more accurate than where unmeasured estimates are used.

The **water table fluctuation (WTF)** method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. Recharge is calculated as (Healy and Cook, 2002):

$R = S_y\ dh/dt = S_y\ Dh/Dt$

where:

S_y is specific yield

h is water table height; and

t is time

The water table fluctuation method is simple to implement, but relies on good estimates of aquifer properties, and can only be applied where there is no groundwater abstraction, or where abstraction can be reliably accounted for.

Global recharge estimates

At a global scale, Döll and Fiedler (2008) provide estimates of long term average diffuse groundwater recharge based on the WaterGAP Global Hydrology Model. The model is run with a daily time-step at a spatial resolution of 0.5°, and is driven by gridded precipitation data. Model parameters are adjusted to match observed long-term average river discharge at more than 1000 gauging stations around the world.

Artificial Recharge

Artificial recharge is the planned, human activity of increasing natural recharge (or infiltration of surface waters into aquifers) with the aim of increasing the amount of groundwater available. Other names for this or related activities are Managed Aquifer Recharge and Aquifer Storage and Recovery. The use of sand dams to artificially increase the potential storage volume for groundwater is one related activity.

Some methods of artificial recharge are simple and have been used for many hundreds or even thousands of years. More technical engineered methods have been used for decades around the world. Artificial recharge or Managed Aquifer Recharge (MAR) technology is flexible and can be applied to many different scales and purposes. However, it can't be used everywhere - aquifer conditions must be suitable, and there must be excess surface water available to recharge.

Some resources with more information are:

- **IGRAC - Managed Aquifer Recharge**

- **IAH - Managed Aquifer Recharge**

- **UNEP** - Sourcebook of Alternative Technologies for Freshwater Augumentation in Some Countries in Asia (Chapter 3.10: Artificial Recharge of Groundwater).

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