Quantitative groundwater recharge estimation

The process of groundwater recharge can be quantified by

- ***Forward*** approaches estimating the infiltration with water balance approaches of the soil or other process-oriented infiltration models
- ***Backward*** approaches estimating recharge from the *resulting* change of storage in the aquifer, water level responses or space- and time-integrating isotope and hydrochemical characteristics of the groundwater. Also fitting of groundwater models is based on the resulting groundwater levels.

The first step should always be an analysis of the hydrological and geological environment. A conceptual model (Hydrogeological Model) of how recharge takes place and of how groundwater flows should be established *before* methods are chosen and before data are collected. The relative importance of direct and indirect recharge mechanisms is a major criterion for the choice of forward or backward estimation methods. If direct recharge is the dominant recharge mechanism, the forward numerical or experimental analysis of vertical moisture flow is a suitable approach. Water balance methods and solute profile methods can be applied.

If indirect recharge mechanisms are dominant, runoff generation and distribution become important, controlling riverbed infiltration. Preferential recharge areas or lineaments (river sections) need to be identified. In this context isotope and hydrochemical indicators as well as inverse methods become helpful tools and have been used for the delineation of favourable recharge areas in complex terrain. If the geological conditions are favourable, recharge rates can also be derived from water level fluctuations or from basin outflow (base flow).

1.4 Forward methods

A classic approach of direct forward recharge estimation is based on the climatic or soil water balance. Any water balance approach requires a definition of a hydrological system for which the individual components of the hydrological cycle are balanced. This may be a vertical soil column, a river reach with defined inlet, and/or a river basin. For the chosen system, all inflows are integrated and added, net change in storage is accounted for, and all the water losses are subtracted in order to obtain groundwater recharge as the resulting term.

1.4.1 Distributed and lumped climatic and soil water balance methods

For a vertical soil column, the discrete form of a water balance formula writes as:

$$R(t) = P(t) - ETP(t) - Q(t) \pm \Delta S$$

with *R(t)* as recharge, *P(t)* precipitation, *ETP(t)* evapotranspiration, *Q(t)* runoff and ΔS change in water storage. A model of hydrological processes between the atmosphere and the soil zone can be used as a basis for computing daily soil water balances and percolation rates. Such models, called SVAT models (Soil-Vegetation-Atmosphere-Transfer) are now also available as distributed models with GIS interface (ARNOLD ET AL., 1998, ARNOLD & ALLEN, 1992).

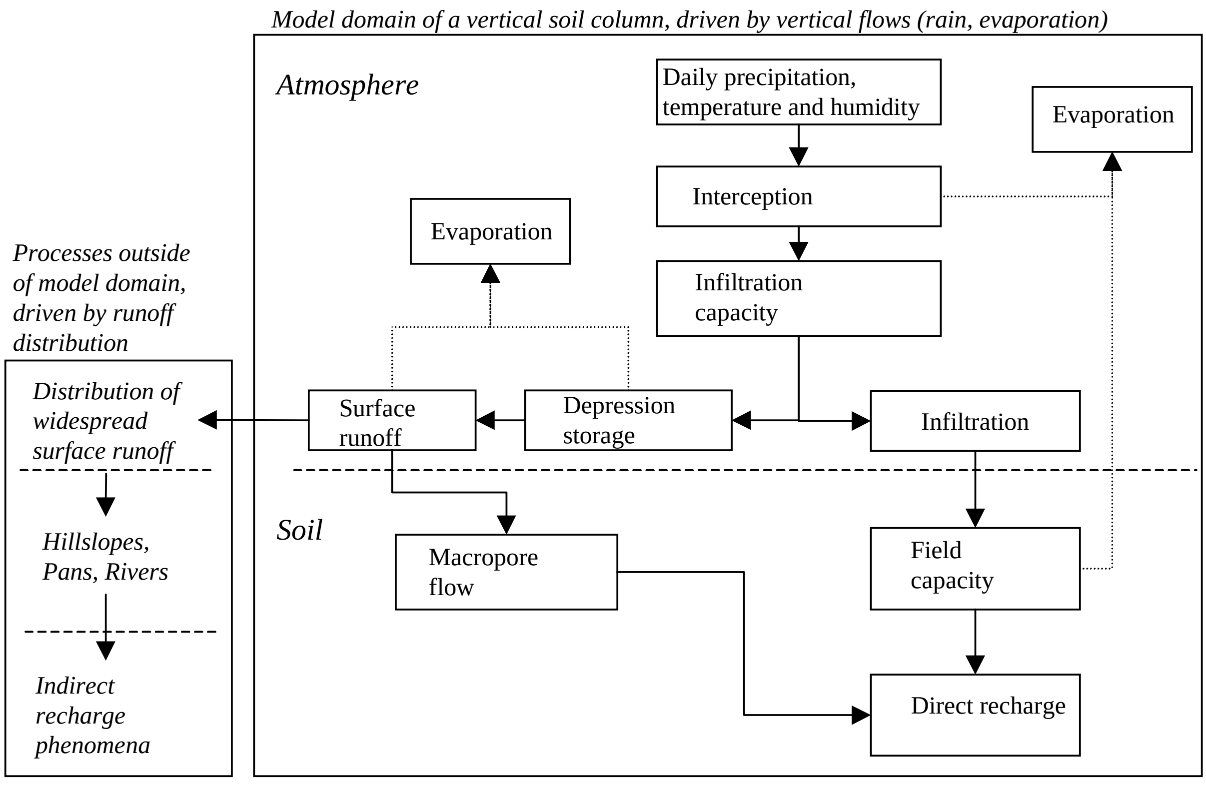

Figure 1 Flow chart representing the water balance model programmed with daily input parameters (rainfall and evaporation in mm), constant parameters (interception, infiltration capacity, field capacity, macropore flow factor), and computed daily data (infiltration, surface runoff, direct recharge).

SVAT models can be used for the computation of daily recharge. Daily rainfall, temperature and relative humidity or pan evaporation are needed as input parameters. Actual transpiration is deduced from actual soil moisture storage on a daily basis. Recharge is produced when the soil moisture reaches or exceeds field capacity. The computed runoff inducing indirect recharge by transmission losses can be accounted for.

1.4.2 Flow estimation based on Darcy's law

The flow estimation based on Darcy requires rather precise hydrogeological data on the gradient and on the hydraulic conductivity. Hydraulic conductivity being difficult to estimate even in terms of orders of magnitude, the recharge estimate can hardly be more precise. The Darcy equation should therefore be used to check results rather than to base direct estimations on it.

1.5 Backward estimation

Any backward estimation is based on analysing the effects of groundwater recharge, such as groundwater level fluctuations and isotopic or hydrochemical properties. Also the analysis of stream flow data can be used provided that the underlying assumptions of this method are met and that the contribution from aquifer discharge can be separated with adequate methods.

1.5.1 Base flow analysis

If – due to the geological conditions – the total amount of groundwater re-appears as spring flow, the recharge can be derived from the base flow. A discharge separation is required. After the separation of groundwater outflow from the stream flow, the groundwater flow is integrated. This method is based on the assumptions that a) there exist steady state conditions and b) that deep percolation is negligible or known. *Therefore it is only applicable in adequate geological conditions that correspond to these assumptions.* Daily stream flow data is needed.

1.5.2 Groundwater level fluctuations

Groundwater level fluctuations indicate the response of an aquifer to groundwater recharge and can be de-convoluted to recharge time series.

For a homogeneous, unconfined aquifer the proportionality factor between groundwater level changes and recharge is given by the effective porosity p of the column affected by groundwater level changes. High seasonal variability of rainfall and distinct recharge events facilitate the isolation of water level rises induced by groundwater recharge. While recharge is characterized by episodic events, natural water losses occur continuously. During periods when the rate of recharge approaches zero, water level decline reflects the net lateral groundwater flow (Figure 2). The difference between predicted and actual groundwater levels can be transformed into recharge, if the effective porosity is known and constant for the range of water level changes. Problems arise from deviations of the basic assumptions (zero flow conditions) and from the difficulty to determine the porosity.

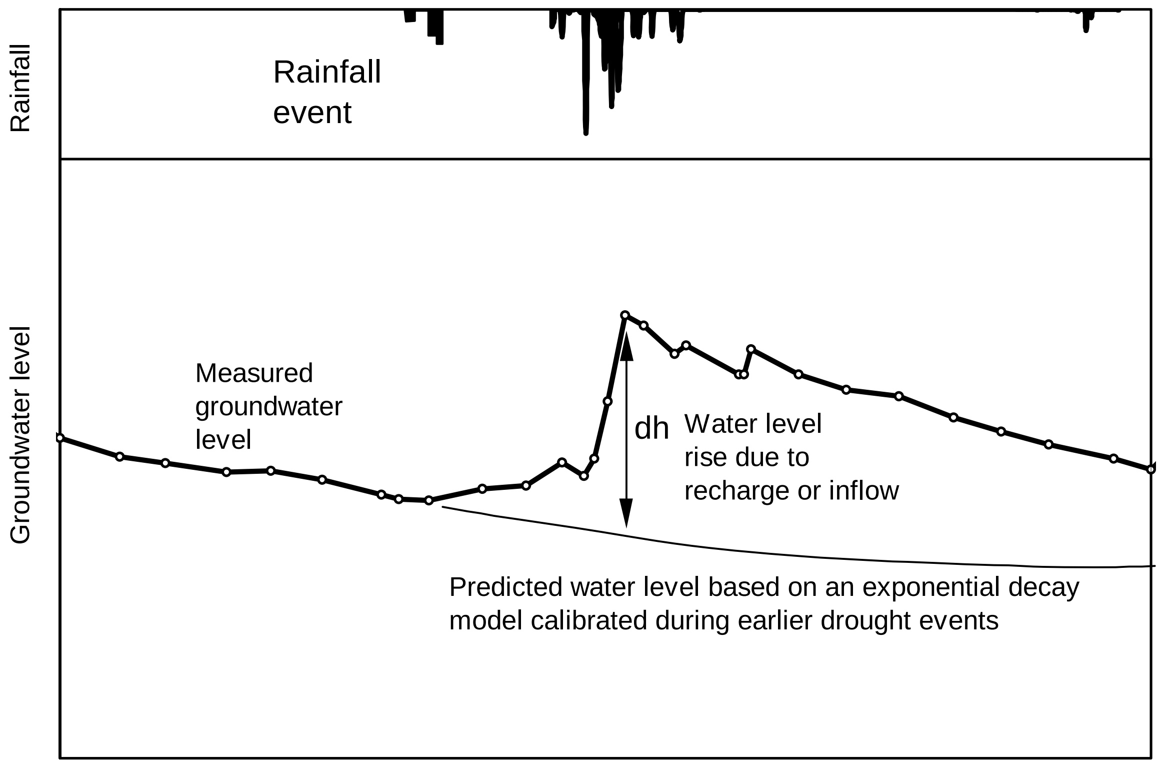

Figure 2 The water level fluctuation method: during periods without recharge (dry seasons) the water level decline is modelled and a predicted water level without recharge is computed. The deviation of the observed water level from this value represents the sum of lateral subsurface inflow and of recharge by percolation.

1.5.3 Groundwater flow models

Groundwater flow models are used to numerically solve the saturated flow equations. The specification of groundwater recharge is one of the boundary conditions. It has been proposed to use groundwater recharge as a fitting parameter and to derive recharge rates from groundwater flow models. This method can only yield reliable results if the conceptual flow model and the other parameters used in the groundwater model can be determined with accuracy. Often, the other parameters such as aquifer thickness, porosity, leakage factors, lateral inflows or hydraulic conductivity can only be roughly estimated or are not known - this affects the reliability of the recharge estimations derived from such models. In fact groundwater models require recharge estimations based on independent methods. In a following step, they can be used and represent a good tool for *validating* regional recharge estimates.

1.5.4 Isotope methods for groundwater recharge estimation

Isotopes can be used in different ways for the backward estimation of groundwater recharge. It is useful to distinguish methods characterizing the recharge process in the unsaturated zone and methods that are based on isotope analyses of groundwater. The advantage is that they give measured evidence and that isotope methods yield time and space integrated information: Processes over longer time periods and larger areas are averaged by mixing processes. For the interpretation of results it is important to correctly represent these mixing processes.

1.5.4.1 Oxygen-18 time series investigations

Oxygen-18 time series can be used to identify very young groundwater components. Since the signal of oxygen-18 is changing seasonally and converges to a stable weighed average, changes in oxygen-18 in time indicate a young recharge component.

1.5.4.2 Age determination along flow paths

Age indicators, such as tritium, carbon-14, krypton-85, fluorinated hydrocarbons (FHC) can be studied along flow paths. From the 'ageing' of groundwater along flow paths, the flow velocity can be estimated. The advantage of these methods is that they yield measured evidence whether the ground water is young and has a high turnover or whether it is old having a slow turnover and being well protected against pollution. Difficulties can arise from not considering the hydro-geological conditions and from neglecting borehole effects.

An overview of the most common methods is given in table 1 (next page). This table also lists the data requirements, the optimal climatic and geologic realm of application and further advantages and disadvantages. Finally, the expected results are presented.

Name of method	Time scale			Spatial scale			Climatic Realm				Geo-Environments				Recharge types covered		Required field work				Required Data							Available Software			Applications in Brazil				Results				
	< 1 year	1-50 years	> 50 years	Local	Basin	Regional	Tropical	Humid	Semi-arid	Arid	Sediments	Hard-rock	Karst	Human impact	Direct	Indirect	Reconnaissance	Sampling	Measurement	Construction	Rainfall	Runoff	Water levels	Aquifer data	Landuse data	Isotopes	Chemistry	Standard (Spreadsheet)	Commercial	Scientific	a. Local application	b. General GAS study	c. Operational method	Not documented	Discrete Time Steps	Discrete Grids (Maps)	Transfer to side-basins	Parametric method	Allows Scenarios
Experimental methods																																							
Lysimeter	+	-	-	+	-	-	+	+	o	-	+	-	-	o	+	-		o	+	+	+	-	-	-	+	o	o	-	-	+	1	-		+	+	-	+	-	-
Tensiometer	+	-	-	+	-	-	o	+	o	-	+	-	-	o	+	-	-	+	+	+	+	-	-	-	+	o	o	-	+	+	2	-			+	-	-	-	-
Soil water balance																																							
Soil water balance	+	o	-	+	+	o	+	+	o	-	+	-	-	+	+	-	+	-	-	-	+	+	+	+	+	-	-	o	o	+	3				+	+	+	+	+
Chloride method	o	+	O	+	o	-	-	o	+	+	+	+	+	o	+	+	+	+	+	-	+	-	-	-	-	-	+	-	-	+	4			+	+	-	-	+	-
Hydrologic water balances for different balance units																																							
Water works data	+	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	-	-	-	+	-	-	-	-	+	-	-	5				+	-	-	-	o
Spring discharge	+	-	-	+	+	-	+	+	o	-	+	+	+	+	+	+	+	-	+	o	o	+	-	-	-	-	-	+	-	-	6				+	-	-	-	-
Base flow	+	+	O	o	+	o	+	+	+	-	+	+	+	+	+	+	+	-	+	-	+	+	-	-	-	-!	-!	+			7a	7b	7c		+	-	-	+	-
Aquifer parameters and storage changes																																							
Water level change	+	+	-	+	+	o	+	+	+	+	+	o	o	+	+	+	+	-	+	-	+	-	+	+	-	-!	-!	+		+	8				+	o	-	+	-
Aquifer data (Darcy)	-	+	+	-	+	o	+	+	+	o	+	o	-	+	o	+	+	-	-	-	-	-	+	+	-	-!	-!	+			9a	9b			-	-	-	o	-
Aquifer model	o	+	+	o	+	o	+	+	+	o	+	+	-	+	+	+	+	-	+	-	-	+	+	+	-	-!	-!		+		10a	10b			+	+	-	o	+
Isotope and hydrochemical methods																																							
^{18}O stable isotope time series	+	-	-	o	+	o	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	o	-	-	-	+	o	-	-	+	11				+	-	-	-	-
Tritium, ^{85}Kr, FHC, SF_6, other tracers	-	+	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	o	o	o	-	+	o	+	+	+	12				-	-	-	+	o
^{14}C dating / mixing	-	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	o	o	o	-	+	o	+	+	+	13				-	o	-	+	o
Development of hydro-geological concept models																															14a	14b	14c						

Table Overview of the most common methods for groundwater recharge estimations and their properties