



Sustainable Groundwater Management: Concepts and Tools

Briefing Note 2

Characterization of Groundwater Systems key concepts and frequent misconceptions

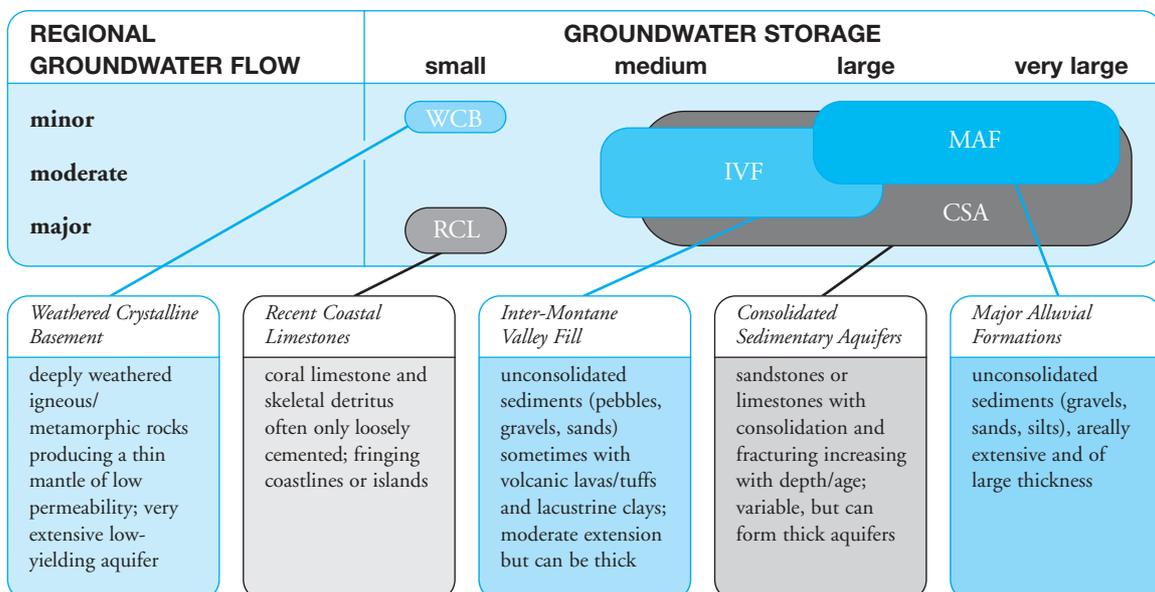
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How do aquifers differ from one another?

- An aquifer is a geological formation capable of yielding useful groundwater supplies to wells and springs. All aquifers have two fundamental characteristics: a capacity for groundwater storage and a capacity for groundwater flow. But different geological formations vary widely in the degree to which they exhibit these properties (Figure 1) and their areal extent can vary with geological structure from a few km² to many thousands of km².
- The most significant elements of hydrogeological diversity (Figure 1) are:
 - major variation of aquifer unit storage capacity (storativity), between unconsolidated granular sediments and highly-consolidated fractured rocks
 - wide variation in aquifer saturated thickness between different depositional types, resulting in a wide range of groundwater flow potential (transmissivity).

Figure 1: Summary of key properties of the most widely-occurring aquifer types





How does groundwater flow?

- The vast storage of many groundwater systems (much larger than that of the biggest man-made reservoirs) is their most distinctive characteristic. In consequence most groundwater is in continuous slow movement (Figure 2) from areas of natural aquifer recharge (from rainfall excess to plant requirements) to areas of aquifer discharge (as springs and seepages to watercourses, wetlands and coastal zones).

MYTH ▶ 'groundwater normally flows in underground rivers'

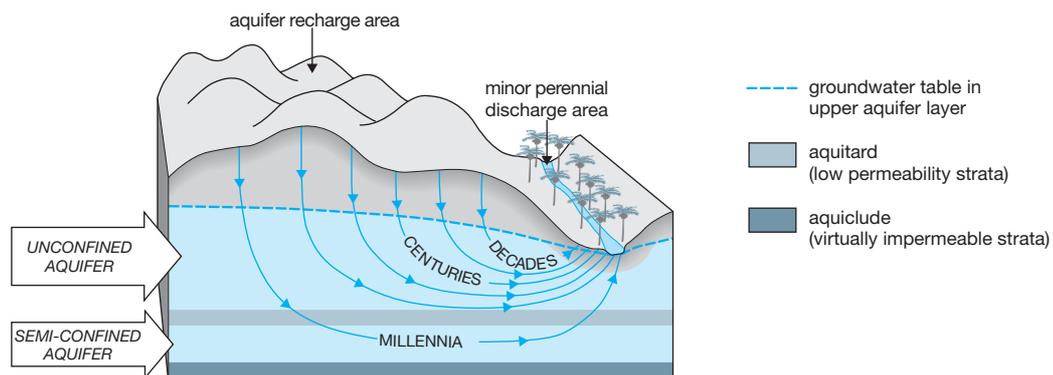
REALITY ▶ *this is the exceptional case, restricted to certain limestones and other rocks with solution caverns, and flow generally takes place in a myriad of interconnected pores or fractures*

- Aquifer storage transforms highly variable natural recharge regimes into more stable natural discharge regimes. It also results in groundwater residence times that are usually counted in decades or centuries (Figure 2) and sometimes even in millennia, with large volumes of so-called 'fossil groundwater' (a relic of past episodes of different climate) still being held in storage.
- Where aquifers dip beneath much less permeable strata, their groundwater becomes confined (to varying degrees) by overlying layers. This results in a corresponding degree of isolation from the immediately overlying land surface, but not from the groundwater system as a whole. Drawdown induced by pumping from the confined section of an aquifer is often rapidly propagated to the unconfined section. In various hydrogeological settings, shallow unconfined and deep confined aquifer layers can be superimposed (Figure 2) with leakage downwards and upwards between layers according to local conditions.

MYTH ▶ 'by drilling wells deeper new groundwater resources can be tapped'

REALITY ▶ *deeper freshwater formations may be encountered, but abstracting their groundwater more often results in induced leakage from overlying aquifers than interception of major independent groundwater flow at depth*

Figure 2: Typical groundwater flow regime and residence times of major aquifers under semi-arid climatic regimes

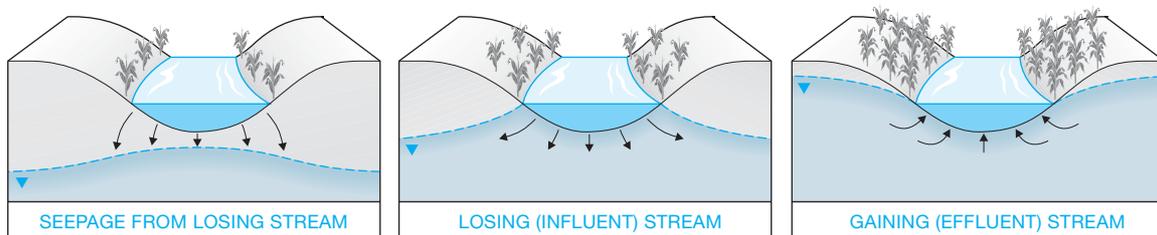




What is the relationship between groundwater and surface water?

- Diagnosing the relationship of surface water to an underlying aquifer is an important component of groundwater system characterization. It is important to distinguish between:
 - streams and rivers on which an aquifer is dependent as a significant source of its overall recharge
 - rivers that in turn depend significantly on aquifer discharge to sustain their dry-weather flow.
- The three most common relationships are presented in Figure 3, although it should be noted that in some cases rivers may fluctuate seasonally between two of the conditions depicted.

Figure 3: Spectrum of possible relationships between surface watercourses and underlying groundwater systems



Why is the estimation of aquifer replenishment important?

- Contemporary aquifer recharge rates are a fundamental consideration in the sustainability of groundwater resource development. Furthermore, understanding aquifer recharge mechanisms and their linkages with land-use is essential for integrated water resources management.
 - The quantification of natural recharge, however, is subject to significant methodological difficulties, data deficiencies and resultant uncertainties because of:
 - wide spatial and temporal variability of rainfall and runoff events
 - widespread lateral variation in soil profiles and hydrogeological conditions.
- Nevertheless, for most practical purposes it is sufficient to make approximate estimates, and refine these subsequently through monitoring and analysis of aquifer response to abstraction over the medium term.

MYTH

‘average rates of aquifer recharge are constant’

REALITY

this commonly-accepted paradigm can be false and lead to serious ‘double resource accounting’ in more arid regions—recharge rates vary with riverflow diversion or control, modifications to surface water irrigation, changes in natural vegetation or crop type in recharge areas, reduction in leakage from urban water-supply networks and in-situ wastewater percolation, lowering of water-table, etc.

- A number of generic observations can be made on aquifer recharge processes:
 - areas of increasing aridity will have a much lower rate and frequency of downward flux to the water-table, with direct rainfall recharge generally becoming progressively less significant than indirect recharge from surface runoff and incidental artificial recharge arising from human activity
 - estimates of the direct rainfall recharge component are almost always more reliable than those for the indirect component from runoff recharge.



How can the 'safe yield' of an aquifer be defined?

- All groundwater flow must be discharging somewhere, and abstraction will reduce these discharges. But the source of groundwater pumped can be complex (Figure 4). So-called 'safe yield' is clearly bounded by the current long-term average rate of aquifer recharge, although should also consider:
 - value judgements about the importance of maintaining (at least a proportion of) some of the natural discharges from the aquifer system
 - consideration of consumptive use and catchment export, as opposed to local non-consumptive uses which result in the local generation of an effluent.

MYTH

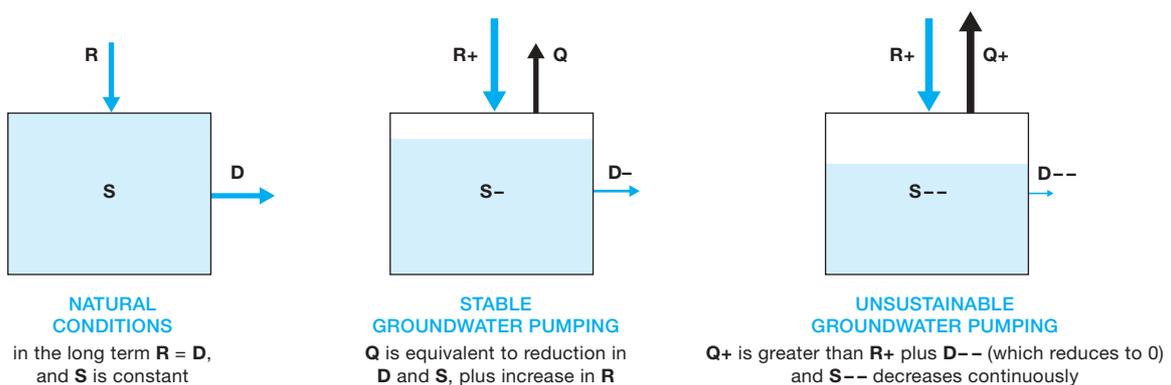
'the average rate of aquifer recharge can be taken as its safe yield'

REALITY

this 'rather persistent fantasy' does not consider the need to maintain aquifer discharge or water-level in the interest of other water users, aquatic/terrestrial ecosystems and/or preventing coastal saline intrusion, and the expression 'safe yield' is often interpreted far too simplistically

- Nevertheless maximum tolerable rates of abstraction need to be defined, and thus resource evaluation must distinguish between:
 - discharge to freshwater systems required to sustain downstream water-supply or river ecosystems
 - discharge via natural vegetation, including that sustaining ecologically and/or economically valuable freshwater wetlands and brackish lagoons
 - discharge to saline areas, including coastal waters, salt lakes and pans
 and make allowances for those parts of these discharges which need to be conserved.

Figure 4: Conceptual effects of abstraction on the groundwater resource balance



When can an aquifer said to be 'overexploited'?

- The term 'aquifer overexploitation' is an emotive expression not capable of rigorous scientific definition. But it is a term which water resource managers would be wise not to abandon completely, since it has clear register at public and political level. Some regard an aquifer as being overexploited when its groundwater levels show evidence of 'continuous long-term' decline.



MYTH

▶ **'falling groundwater levels always imply aquifer overexploitation'**

REALITY

▶ *all groundwater development involves drawdown and this process can have a time-lag of many years before a new equilibrium is established in large aquifers of low transmissivity/storativity ratio—this could be mistaken for continuously-declining groundwater levels in some cases*

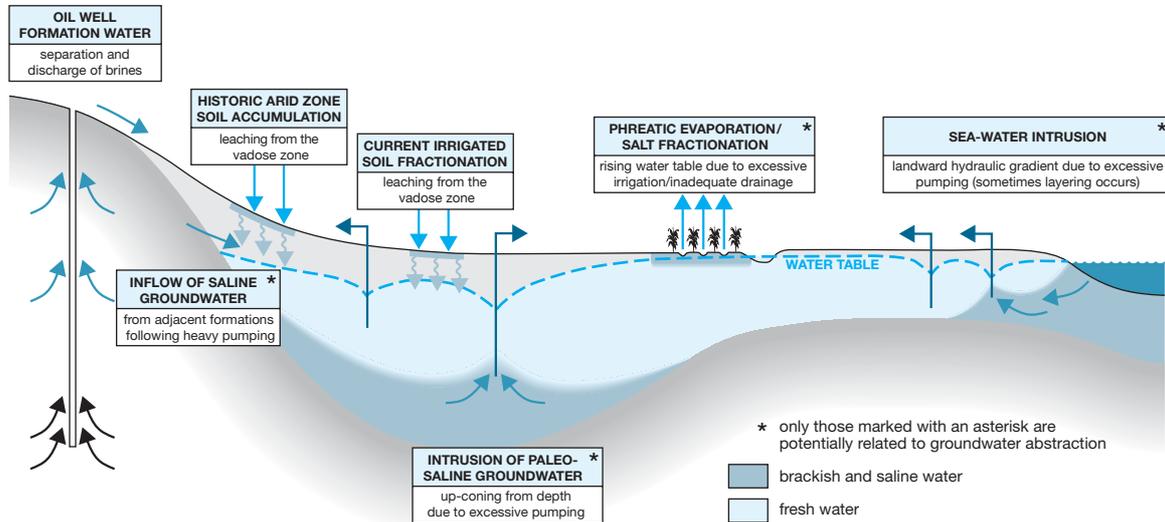
- Others take it to mean that the long-term average rate of groundwater recharge is less than abstraction. Even this definition may not be workable because of:
 - the problem of specifying over what period and which area the groundwater balance should be evaluated, especially in more arid climates where major recharge episodes occur once in decades and pumping effects may also be very unevenly distributed
 - more general uncertainty about aquifer recharge mechanisms and rates, as a result of hydrogeological complexity and inadequate field data
 - the fact that major temporal variation in aquifer recharge components can occur, such as those associated with lowering water-table, long-term climatic trends and human activities.
- In practice, when speaking of aquifer overexploitation we are invariably much more concerned about the consequences of intensive groundwater abstraction (Figure 4) than in its absolute level. Thus the most appropriate definition is probably an economic one: that the **'overall cost of the negative impacts of groundwater exploitation exceed the net benefits of groundwater use'**, but of course these impacts can be equally difficult to predict and to cost.
- It is important to stress, in this context, that some of these consequences can arise well before the groundwater abstraction rate exceeds long-term average recharge. Thus the way in which a given situation is interpreted will vary with the type of aquifer system involved—that is with volume of exploitable storage and susceptibility to irreversible side-effects during short-term overdraft.
- Amongst the most critical of potential impacts from intensive aquifer development (Figure 5) is groundwater salinization. This will be terminal for both potable water-supply and agricultural irrigation uses. However, it is important to diagnose the cause of groundwater salinization since it can be caused by various mechanisms (Figure 6), only some of which are aquifer pumping related.

Figure 5: Consequences of excessive groundwater abstraction

REVERSIBLE INTERFERENCE	IRREVERSIBLE DEGRADATION	
<ul style="list-style-type: none"> • pumping lifts/costs increase • borehole yield reduction • springflow/baseflow reduction 	<ul style="list-style-type: none"> • phreatophytic vegetation stress (both natural and agricultural) • aquifer compaction and transmissivity reduction 	<ul style="list-style-type: none"> • saline water intrusion • ingress of polluted water (from perched aquifer or river) • land subsidence and related impacts (aquitard compaction)



Figure 6: The possible origins of groundwater salinity and mechanisms of aquifer salinization



- Groundwater is never a strictly non-renewable resource, but nor is it everywhere fully renewable in the time-frame of current development. There are thus some circumstances where exploitation on non-renewable groundwater resources (mining of groundwater reserves) may be considered (or has occurred unexpectedly) and requires systematic evaluation.

Further Reading

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Publication Arrangements

The GW•MATE Briefing Note Series has been designed by Words and Publications, Oxford, UK, and published by the World Bank, Washington D.C., USA. It is also available in electronic form on the World Bank water resources website (www.worldbank.org/gwmate) and the Global Water Partnership website (www.gwpforum.org).

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Funding Support



GW•MATE (Groundwater Management Advisory Team) is a component of the Bank-Netherlands Water Partnership Program (BNWPP) using trust funds from the Dutch and British governments.

