Sustainable Groundwater Management
Concepts & Tools

Briefing Note Series Note 16

Groundwater Resource Accounting
critical for effective management in a 'changing world'

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Why are groundwater balances often found inadequate for resource management ?

- Groundwater resource accounting provides the essential technical foundation for making sound management decisions. While normally expressed in terms of the 'groundwater balance' of a specified 'groundwater body' – between recharge (replenishment) and discharge (including use) – it is most important to realise that it is the ***detailed understanding and breakdown of the components of this balance which provide vital information for management.***

- It is precisely because this breakdown is often insufficient or incorrect that groundwater balances are frequently found inadequate for resource management purposes – and this is commonly associated with the following considerations :
  - ***on the 'recharge side' of the equation*** – failure to recognise the level of dependence upon land-use practices or upon streambed infiltration in a river system, both of which may be subject to temporal change
  - ***on the 'discharge side' of the equation*** – failure to recognise the level of non-consumptive use and 'return flow' implicit in a given type of major groundwater abstraction or the level of dependence of a given aquatic or terrestrial ecosystem on direct transpiration from the groundwater body.

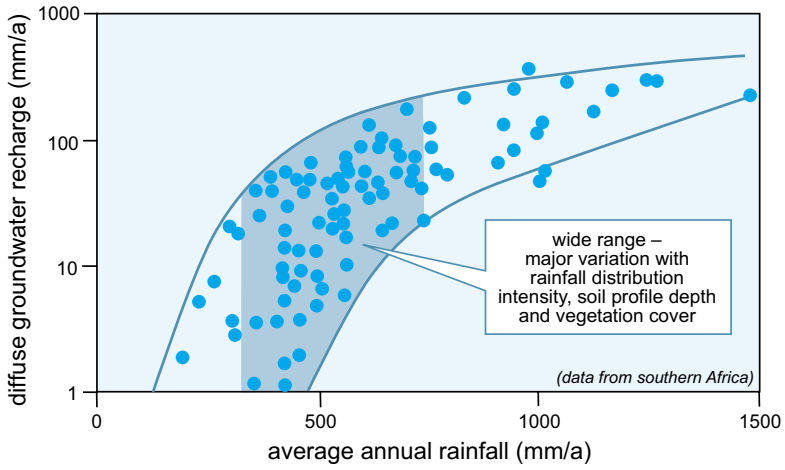
- In this context 'questions of scale' – the spatial and temporal definition of the 'groundwater balance calculation' – are equally important. It is thus recommended :
  - to elect carefully the 'time basis' for calculation in climates where the incidence of major rainfall (and therefore of natural recharge) episodes has a long period of return, taking into consideration the potential effect on the groundwater body of temporal imbalances
  - to define the 'groundwater body' carefully in relation to the resource management issues that need to be addressed – a 'groundwater body' being a flow-boundary delimited part of a large aquifer system or a grouping of small interdependent aquifer units
  - to relate the 'groundwater body' to the corresponding larger hydrological unit (usually river basin), recognising its potential role of providing 'baseflow' (especially dry-weather flow) in that river.

How should we evaluate the components of groundwater replenishment ?

- Detailed scientific research on groundwater recharge processes under 'natural conditions' reveals that there is no simple relationship between average annual precipitation (rainfall) and the amount of deep infiltration to aquifers (Figure 1), especially in more arid climatic settings, because recharge is also highly dependent on other widely-varying factors :
  - intensity of rainfall events (and their temporal distribution)
  - presence (or absence) of lower permeability layers in the soil profile
  - capacity of the soil profile to retain infiltration and associated vegetation cover to utilise it later during the subsequent 'dry season'.

  In consequence estimates of the frequency and rate of 'natural diffuse groundwater recharge' in drier climates always need to be carefully checked – especially in situations of deep soil profile where the natural vegetation cover will probably have evolved to include very deep-rooted and drought-resistant species (usually small trees and bushes) capable of drawing moisture from many metres depth and effectively 'capturing' all infiltration except that associated with exceptional rainfall events.

Figure 1: The reduction of diffuse recharge rates to groundwater with decreasing rainfall



- Moreover, other recharge mechanisms are likely to be operative – especially indirect rainfall recharge from local surface run-off in ephemeral streambeds (Table 1), which can become predominant in more arid climates but difficult to estimate with high confidence and precision.

- A systematic approach to groundwater recharge estimation, together with the types of data required, is provided by Table 1 – and it is important to stress that :
  - considerable professional experience and judgement is required to obtain reliable results, and to appraise uncertainty and potential error effectively
  - a careful breakdown of the components of recharge, and understanding of their linkages and dependencies, is vital for the diagnosis of appropriate management measures and interventions (as will be detailed in succeeding sections)
  - recharge can be strongly influenced by (and dependent upon) human activity at the land surface (Table 1), which in turn can exhibit major temporal changes.

Thus (even disregarding the potential effects of accelerated climate change) it is not adequate to assume without questioning that groundwater recharge processes exhibit 'hydrological stationary'. Moreover, in groundwater resource management recharge estimation should be regarded as an iterative process in which evaluations are refined over time by monitoring and modelling of the groundwater system concerned, adjusting management policy accordingly.

Table 1: Breakdown of groundwater recharge evaluation required for resource management purposes**

SOURCE OF RECHARGE	COMMENTS ON RECHARGE MECHANISM	DATA REQUIRED FOR ESTIMATION	SPECIAL SITUATIONS TO NOTE
BY 'NATURAL PROCESSES'			
Direct (Diffuse) Infiltration of Excess Rainfall	can involve both matrix and preferential flow components but reasonable bulk estimation of deep infiltration to groundwater and (where appropriate) surface run-off possible using simple numerical model	• daily (weekly) rainfall • soil infiltration capacity • soil moisture retention • vegetation cover • daily evapotranspiration	major vegetation change exerts a significant influence (eg. deforestation tends to decrease recharge if soil compaction and sloping ground involved, but otherwise to increase recharge)
Indirect Rainfall Recharge from Local Surface Run-off	when local surface run-off occurs but subsequently infiltrates from ephemeral streambeds	• stream run-off observations post major rainfall events	tends to be associated with high-intensity rainfall events characteristic of more arid climates
Seepage from Main Rivers & Lakes	occurs where main rivers and/or lakes are in 'structural setting' making them influent to groundwater - seepage rates can be estimated by empirical formulae or a simple numerical model	• differential river gauging • temporal lake fluctuations and associated data	important to appreciate that higher riverbed seepage rates likely under clear-water conditions downstream of impounding reservoirs and sediment traps (but such structures may also be used to divert water from the river) ***
FROM HUMAN ACTIVITIES			
Infiltration of Excess Agricultural Irrigation from surface water source / from ground-water source	seepage during canal distribution and field application, with rates varying widely according to extent and lining of canals and irrigation technology	• depth and timing of irrigation lamina • crop consumptive use data, together with appraisal of non-beneficial evaporation • irrigation canal differential gauging or wetted area and bed permeability (as appropriate)	irrigation applications have to be incorporated with rainfall data to calculate overall recharge increment – changes from gravity to pressurised application will radically change position (note also different implications according to source of irrigation water)
Urban Seepage from Water Infrastructure from surface water source / from ground-water source	deep infiltration from a variety of sources such as water mains leakage, percolation from in-situ sanitation units, and seepage from main sewers and drains	• night measurements of water mains flow • estimate of proportion of sanitation through in-site units • spot measurements of sewer and drain flows	principal difficulty is establishing whether all 'losses' from urban water infrastructure actually become groundwater recharge (and are not intercepted by tree roots and/or deep drains) – note also different implications according to source(s) of urban water-supply including consideration of private supplies

** *excluding subsurface inflow from other aquifers (whose evaluation is case specific)*
*** *this source of recharge also often subject to temporal change as a result of human activity in surface water catchments*

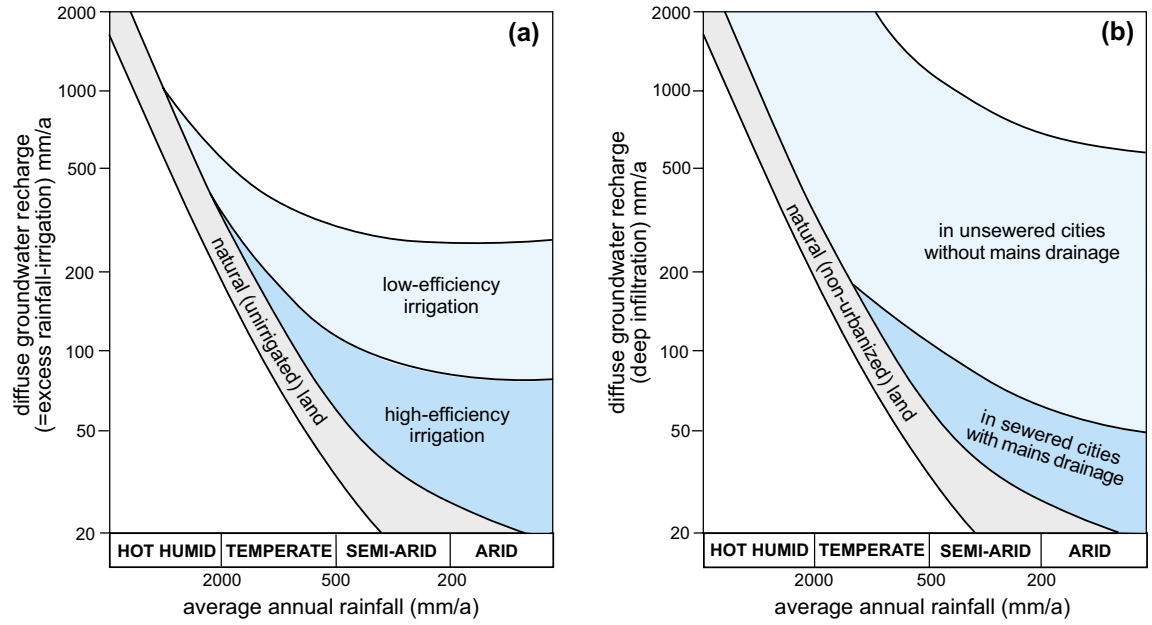
- Geochemical and isotopic (stable and radioactive) analyses of groundwater samples can be very useful for the diagnosis of recharge mechanisms, but specialist knowledge is required to design the corresponding sampling programme and to interpret the results (thus no detail is entered into here). However, it should be noted that when bulk sampling of the aquifer's saturated zone from production waterwells is employed, it will only provide an 'integrated impression' of the sources of recharge involved. But vadose (unsaturated) zone profiling can provide a 'detailed signature' of historic recharge (capable of quantitative interpretation in some cases over periods of decades or centuries) from the immediately overlying land-use, although requires careful interpretation as regards how representative profiles are of larger land areas.

How are groundwater resources closely linked with irrigation water management ?

- For the purpose of groundwater resource management in the more arid regions it is essential to appreciate that overall groundwater recharge rate and quality are intimately linked with irrigation water management. The processes of distributing surface water by irrigation canals and applying it at field level involve potentially high rates of seepage and infiltration loss respectively, which in permeable soil profiles become groundwater recharge. In view of the large land areas under irrigation this widely becomes a major part of total groundwater replenishment – but such recharge can be radically reduced if irrigation canals are lined and/or pressurised irrigation techniques (micro-aspersion or drip) are introduced (Figure 2).

- Where groundwater (rather than surface water) is the principal source of irrigation water, seepage (and other 'losses') during distribution will generally be less – since waterwells are normally located close to fields they irrigate, water delivery is much shorter and indeed often piped. Moreover, although excess

Figure 2 : Typical rates of augmentation of groundwater recharge in the presence of (a) irrigated agriculture and (b) urbanisation



irrigation at field level will result in recycling a 'return flow to groundwater', the local control of (and thus more precise) delivery volumes result in less frequent over-application (especially when unexpected rainfall reduces crop irrigation demand).

- In this context, the term 'irrigation (water) efficiency' is the origin of much misunderstanding. There are various definitions of 'irrigation efficiency' – but in essence it is used to indicate the percentage of irrigation water-supply which is actually transpired by the crop under cultivation (although the irrigation water supplied has variously been interpreted as that 'abstracted from source', 'delivered to field', 'applied to plants', etc). Such definitions have been widely cited in the agricultural literature for more than 50 years, and are often central to the evaluation of how well (or badly) an irrigation system is performing and of recommendations about what should be improved.

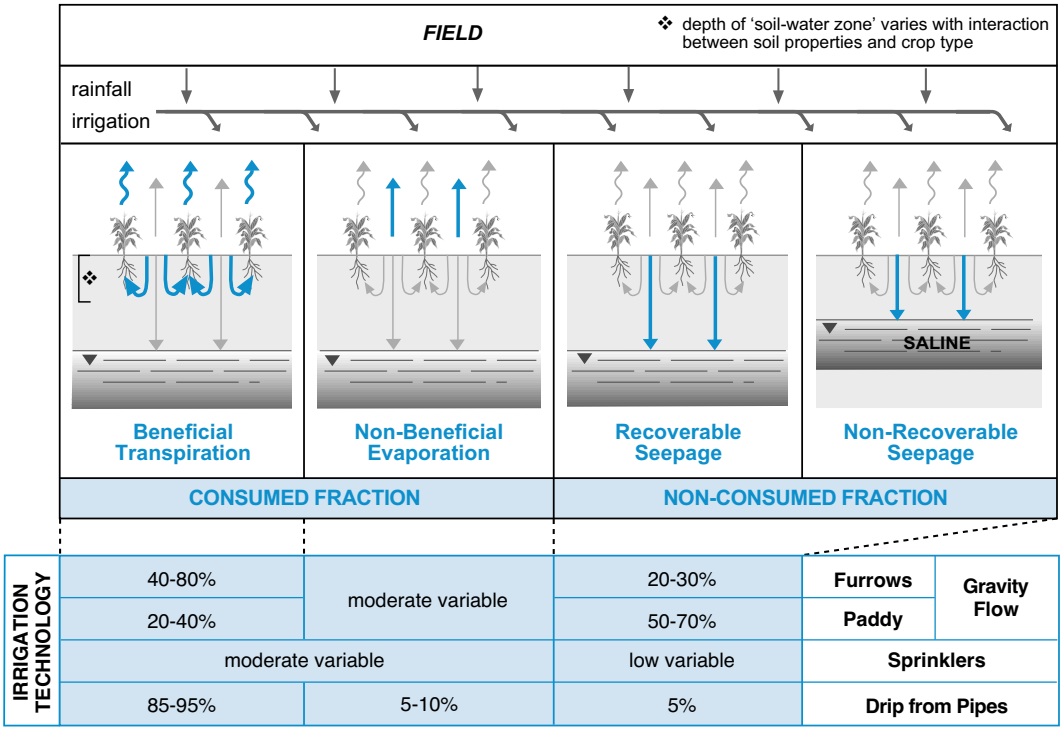
- Clearly the purpose of irrigation in agricultural cultivation is to increase crop production and the direct implication is that crop transpiration must also increase – because for a given climate and crop type, ***biomass generation exhibits an essentially linear relation with crop transpiration*** (although not necessarily related grain or fruit production). And from the farmers' perspective any water that does not contribute to crop production is considered a 'loss' – this entirely legitimate perception explains the origin of the widely-used term 'irrigation efficiency'.

- However, when looked at from the perspective of the groundwater body or the hydrological basin the situation is very different, since a (variable) part of the farmers' 'loss' is returned to underlying groundwater and/or to downstream surface water (depending upon irrigation management and soil profile) – and thus not 'lost'. For improved land and water management it is essential to introduce a more rigorous terminology into the process of soil-water accounting in irrigated agriculture (Figure 3), which permits the impacts of change to be assessed and interventions to be prioritised.

- In reality water reaching an irrigated field by whatever process (rainfall or irrigation with surface water or groundwater) splits into two 'fractions' and a number of 'sub-fractions' (Figure 3) according to interaction between the method of application and the prevailing soil conditions :
  - **a Consumed Fraction** which can be further divided into :
    - ***beneficial transpiration*** consumed by the crop being cultivated
    - ***non-beneficial evaporation*** from wet soil (including limited transpiration by weeds)
  - **a Non-Consumed Fraction** which can be further divided into :
    - ***recoverable seepage*** infiltrating as 'return flow to a freshwater aquifer
    - ***non-recoverable seepage*** infiltrating to a saline aquifer.

- This approach is conceptually much sounder than considering irrigation efficiency and gross losses alone, even if its application will sometimes require professional judgement to overcome data limitations and to address questions such as :
  - do irrigation returns infiltrate to an exploitable aquifer in a meaningful time-frame under very deep water-table conditions
  - does capillary rise also contribute to crop transpiration in conditions of very shallow water-table
  - how usable are the more saline irrigation returns (which will vary with the salt-sensitivity of crops being irrigated).

Figure 3 : Utilisation and fate of water applications to permeable soil – indicating their relationship with groundwater resources and variation with irrigation water management



- Moreover, the importance of context cannot be overstated – for example :
  - spate irrigation deliberately diverts as much flood runoff to fields as possible so as to provoke deep infiltration as a water-conservation measure (since this water would otherwise be non-recoverable as a result of loss to saline inland basins or to the sea)
  - paddy rice cultivation is unique, since viewed at field scale the transpired fraction is relatively low but applications are very high because enough water has to be applied to compensate for seepage and evaporation so as to keep the crop inundated and because of the need for water flows from field-to-field (such that the higher fields supply those 'below').

- In terms of the time basis and spatial framework for accounting respectively – monthly data often have to suffice (although the potential influence of high-intensity rainfall events needs also to be appraised from daily rainfall records) and areas of similar cropping regime and soil profile will need to be delineated. And in respect of related groundwater recharge :
  - seepage from irrigation canals needs to be separately accounted from seepage during irrigation-water distribution from waterwells
  - infiltration of surface-water irrigation excess to crop requirements at field-level needs to be separately accounted from groundwater irrigation excess to crop requirements at field-level

  but conjunctive use of groundwater and surface water for irrigation will complicate the picture.

- Estimates of the 'consumed soil-water fractions' and of non-beneficial evaporation and non-recoverable seepage (Figure 3) will also be needed to indicate possible interventions to save water resources, and this will require sound professional judgement. For any given field situation the type of information required is indicated in Table 2. The field performance of different irrigation technologies cannot be completely generalised – thus the estimates presented in Figure 3 should be viewed as merely indicative of the typical range, since much depends on the maintenance and operation of the system concerned.

- Real water resource savings, which result in more water being available for other users (including environmental flows) and/or for replenishing depleted aquifer storage, can only be achieved by reducing the size of the consumed fractions and/or the non-consumed non-recoverable fraction (Figure 3). The most direct way to achieve this is by restricting the total cropped area under irrigation – preferably whilst concomitantly increasing irrigation-water productivity through the cultivation of higher-value crops in an effort to protect farming profitability and farmer incomes. Other approaches could include :
  - reducing non-beneficial evaporation through more targeted and reduced application of irrigation water and/or use of plastic sheeting or incorporating additional organic material
  - eliminating weeds and any other obvious sources of non-beneficial transpiration
  - switching to cultivation of less water-consuming crops or crop-strains (with shorter growing season, or suited to cooler periods when potential evaporation and transpiration are lower).

  An example of the benefits of modernising irrigation technology is shown in Table 3. This would be considered a success, since the saving in pumping energy was substantial at 50%, but it should be noted that while the overall 'irrigation efficiency' was improved by 38%, the real groundwater resource saving was only 12% (albeit a useful 55 mm/crop).

Table 2 : Summary of data requirements and information sources for estimation of the soil-water balance of irrigated crops

PARAMETER	MEASUREMENT OPTIONS & ESTIMATION METHODS
Irrigation Water Applied	• gauged delivery records, water well pumping hours and rainfall recording devices
Consumed Fraction	• evapotranspiration can be (a) computed from climatic data and crop coefficients (eg. Penman-Monteith, Blaney-Criddle, Hargreaves) (b) measured using evaporation pans combined with crop coefficients (c) estimated from satellite thermal imagery (SEBAL, METRIC) – (a)/(b) indicate maximum potential value for a given crop or plant cover under favorable conditions but this may not be occurring in practice, whilst (c) estimates actual value independent of crop type • for **Consumed Beneficial Sub-Fraction** UN-FAO 56 gives procedures for the partition of transpiration (T) and evaporation (E) for differing irrigation technologies • for **Consumed Non-Beneficial Sub-Fraction** SEBAL-type approaches allow estimation of biomass formation can be used to partition T and E, and by inferring T from biomass relationship E is estimated as residual
Non-Consumed Fraction	• estimated as difference between 'Irrigation Water Applied' and 'Consumed Fraction', with confirmation from groundwater level fluctuations (or field monitoring of drain flows in less permeable soil profiles) • the partition of the **Recoverable & Non-Recoverable Sub-Fractions** is entirely dependent on, and specific to, the local hydrogeological condition

Table 3 : Effect of changing irrigation technology to 'improve irrigation water efficiency' on groundwater recharge – example from an arid region

PARAMETER	IRRIGATION TECHNOLOGY	
	Unlined Canals with Gravity Flood Application	*Piped Distribution with Pressurized Drip Application*
*total rainfall***	130 mm	
*total irrigation water-supply***	460 mm	230 mm
*crop beneficial transpiration***	315 mm	310 mm
*non-beneficial evaporation during distribution***	45 mm	5 mm
*non-beneficial evaporation during application***	25 mm	15mm
*recoverable irrigation distribution returns***	150 mm	20 mm
*recoverable irrigation application returns***	55 mm	10 mm
distribution efficiency	58%	89%
application efficiency	70%	88%
overall irrigation (water) efficiency	40%	78%
*real water resource saving****	12% (55 mm)	
*actual pumpinging energy saving****	50%	

* *data represent a generalized case developed from selected unpublished investigation and monitoring sites on relatively permeable soils in Hebei Province, North China Plain*

** *cumulative during period of cultivation of dry-season wheat crop concerned and expressed as equivalentaverage depth of water over crop cultivated area*

*** *savings resulted when converting from traditional to modern irrigation technology*

- Improved soil-water accounting and real water resource savings will only be achieved through the concerted efforts of water resource agencies and agricultural extension services working in close cooperation with irrigation water-users. Constraining groundwater use is difficult to introduce, and 'positive' interventions that allow farmers to grow higher value crops per unit of water pumped have the perverse implication of making groundwater use, even against increasing pumping lifts, all the more attractive – and should farmers irrigate a greater cropped area with the water considered to have been 'saved', more water is consumed by crops and 'net groundwater abstraction' will increase. Indeed, the reason for a farmer changing technology is rarely to save water, but more often to achieve other (to him) more important benefits including :
  - increasing crop-water productivity and profitability through permitting the cultivation of high-value (water-sensitive) crops
  - facilitating labour saving (at least in some instances)
  - saving of electrical energy or diesel fuel for water pumping.

Which modifications to groundwater recharge widely occur in urban areas ?

- In parallel fashion (with some hydrological similarities to irrigated agriculture) urbanisation introduces a series of complex and evolving changes in groundwater recharge mechanisms, which are today better understood as a result of considerable hydrogeological research and monitoring.

- Although at first sight it might be believed that major urban land-surface impermeabilisation will always result in significant reduction of recharge to underlying unconfined aquifers, in practice this is only very exceptionally the case. This is because urbanisation is invariably also associated with high rates of seepage from the water-based infrastructure due to :
  - substantial rates of leakage from mains water distribution systems
  - return of large volumes of wastewater to the ground via in-situ sanitation
  - seepage from some mains sewerage systems and stormwater drains.

  The integrated effect is usually to outweigh completely the reduction in rainfall infiltration resulting from land-surface impermeabilisation, which explains the elevated groundwater recharge rates (and quality deterioration) widely observed in major urban areas (Figure 2).

- Clearly there are variations in the detail, for example :
  - the effect will be much less marked in situations where local groundwater itself (as opposed to 'imported surface water') is the principal source of municipal water-supply, since (once again) a substantial component of recirculation will be involved with only a very minor proportion of the abstracted groundwater resource being consumed or removed
  - if the underlying aquifer is deep and/or semi-confined not all of the increased urban seepage can reach it as recharge, with some accumulating in 'perched water-tables' from where it may be discharged by tree roots and/or to deep sewers and drains.

Why does the 'discharge side' of the groundwater balance merit equally careful accounting for resource management ?

- Detailed analysis of the 'discharge side' of the groundwater balance is required to develop a clear understanding of the various mechanisms involved, since quantification of these components provides critical information for the formulation of entry points to 'demand-side management' – Table 4 provides a systematic approach to such analysis together with an indication of the types of data required. For reasons explained below, it is recommended that analysis should be initiated by evaluation of the 'human interventions' (groundwater use by waterwell abstraction) and that assessment of the 'natural components' is conducted after this abstraction is compared to estimates of total groundwater recharge.

- A critical assessment of potential errors and uncertainties in the estimation of groundwater abstraction and use is important – given that there will rarely be direct volumetric metering of waterwells. In most instances it will be important to approach such estimation by two independent methods to escape some 'common pitfalls' such as :
  - the volume of permitted or licensed abstraction recorded on groundwater rights (where these have been implemented) can significantly over-estimate or under-estimate actual abstraction, depending on local circumstances and pressures affecting water use
  - conversion of electrical energy consumption (more widely and accurately metered than groundwater use) to groundwater volumes actually abstracted is complicated by the need for complementary information on hydraulic efficiency of pumps (and it may be more useful to use electrical energy data as an indicator of pumping period and combine this with pump production capacity under general condition of use).

Table 4: Breakdown of groundwater discharge evaluation required for resource management purposes

TYPE OF DISCHARGE		COMMENTS ON DISHARGE MECHANISM	DATA REQUIRED FOR ESTIMATION	SPECIAL SITUATIONS TO NOTE
FROM HUMAN ACTIVITIES				
Water Well Abstraction	***Urban Area***	difficult to estimate total volume extracted if basic water well inventory not available and pumping records not maintained by owners	• volumetric metering • electricity consumption • estimated irrigation use • volume licensed • pump capacity and pumping duration	approach using 'type area' surveys with scaling-up according to extension of comparable areas often possible and produces acceptable results – indirect estimation using electric energy or diesel fuel consumption in irrigation areas also possible but assumptions on average pump efficiency necessary
	Rural Area	same applies, but in general water well location is easier and related irrigation use more evident – necessary to have sound estimates of part of crop water requirement provided from groundwater (as opposed to rainfall and surface water)		
BY 'NATURAL PROCESSES'				
Diffuse Transpiration by (a) Wetland Ecosystems & (b) Terrestrial Vegetation (including agricultural crops that do not require land drainage – such as paddy rice and sugarcane)		potential evapotranspiration estimated using basic meteorological data and actual estimates derived from knowledge of vegetation area, type and condition (but uncalibrated estimates subject to considerable error and wide seasonal variation)	• meteorological data for calculation of evapotranspiration • satellite imagery for estimating areas of corresponding vegetation	periodic satellite thermal imagery based on 'energy balance' can be used to estimate total evapotranspiration from relatively small target areas and can provide independent check on discharge estimates
Groundwater Flow to Riverbeds, Lakebeds, Lagoons & Coastal Waters		direct survey and indirect measurement can provide reasonable estimates under favourable conditions (but with more complex hydraulic relations between groundwater and surface water can pose major challenge)	• for rivers differential spot measurements and stream flow gauging • for lakes gauging of level fluctuations compared to evaporation losses	remote-sensing methods based on thermal satellite imagery can be used to identify/confirm discharge zones providing adequate temperature contrast exists
Spring Flow		survey and measurement is traditional method (but unless continuous flow gauging installed subject to large error) – identification of springs from specific aquifer is greatly aided by chemical and isotopic analyses	• terrain maps, aerial photos and satellite images for locations • spot measurements and flow gauging • chemical and isotopic water analyses	biggest problem is coping with seasonal variation because integrated annual estimates required and as such procedures are time-consuming

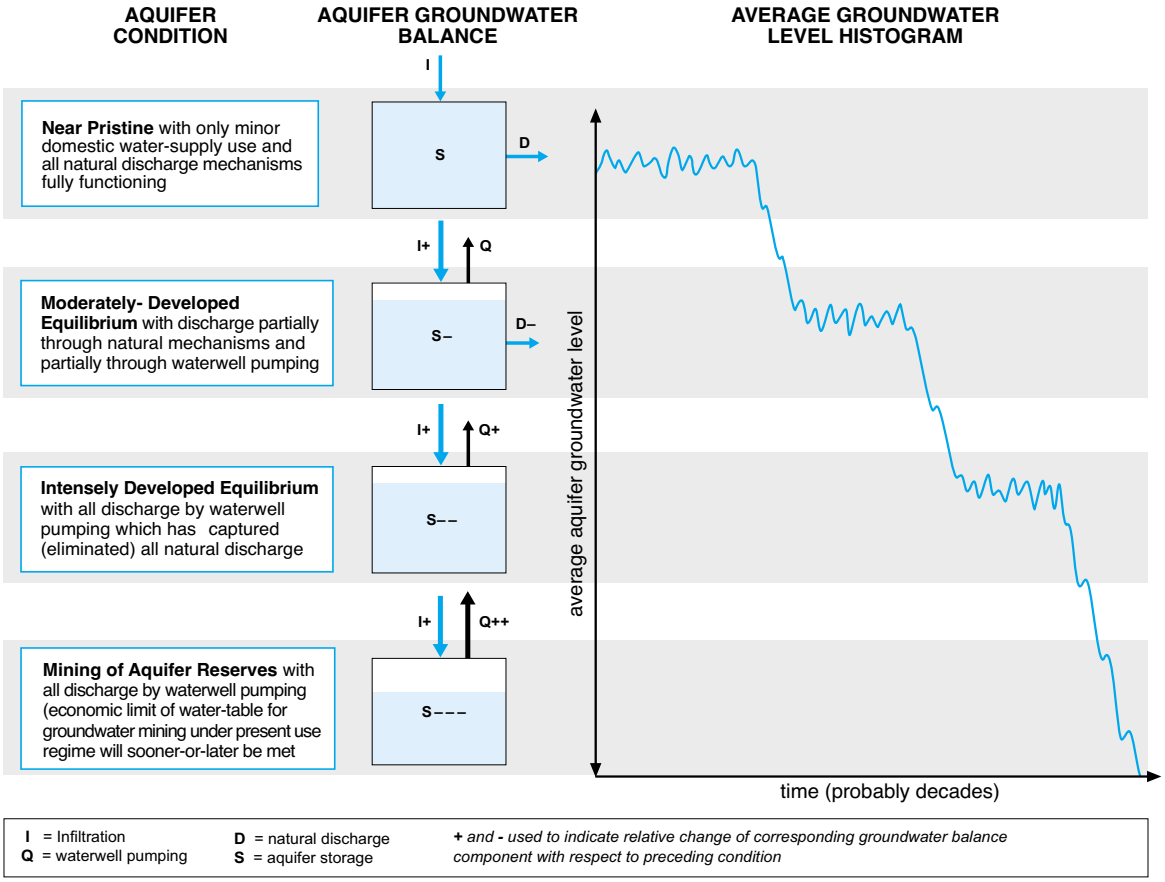
- Estimates based on the actual use of water for the agricultural, industrial or domestic purpose involved can provide valuable cross-checks, but it is necessary to bear in mind that use for :
  - irrigated agriculture will vary widely with rainfall in the corresponding growing season and the losses implicit with the irrigation technique employed (as described above)
  - an industrial process may show marked daily and/or seasonal variation
  - domestic purposes will vary widely with social grouping and ambient temperature, and whether garden watering is involved.

How should we interpret the groundwater resource balance obtained ?

- The rates of 'natural discharge' of groundwater bodies (through the mechanisms detailed in Table 4) will exhibit progressive reduction with the 'stage of groundwater resource development', since in effect almost all waterwell abstraction inevitably will (in 'renewable groundwater resource' scenarios) be at the expense of reduction in natural groundwater discharge. But it should be noted that the process of groundwater development will often at first introduce additional recharge in areas of very shallow water-table where potential recharge was previously 'rejected' because the groundwater body was 'already full'. Thus interpretation of groundwater balances needs to take account of the temporal sequence in Figure 4.

- In completing and interpreting the state of the groundwater resource balance it is necessary to survey and estimate natural discharge through springflow, inflow to riverbeds and wetlands, and direct transpiration by terrestrial ecosystems (Table 4) and assess the extent of any negative consequences of interference and reduction against the benefits of the use of groundwater abstraction via waterwells.

Figure 4 : The stages of groundwater resource development and their impact on the natural discharge of groundwater bodies



- With further increases in abstraction a groundwater body can still achieve hydraulic equilibrium (discharge balanced by recharge), but all natural discharge may have been eliminated by interception from waterwells (Figure 4), although this may represent an unacceptable situation from the standpoint of interests in springflow, baseflow in rivers, and groundwater-dependent ecosystems. In even more extreme cases the rate of sustained waterwell abstraction may significantly exceed the total rate of replenishment and equilibrium will not be achievable – leading to mining of groundwater storage reserves, although this may be socially-acceptable providing appropriate management measures are in place.

Further Reading

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