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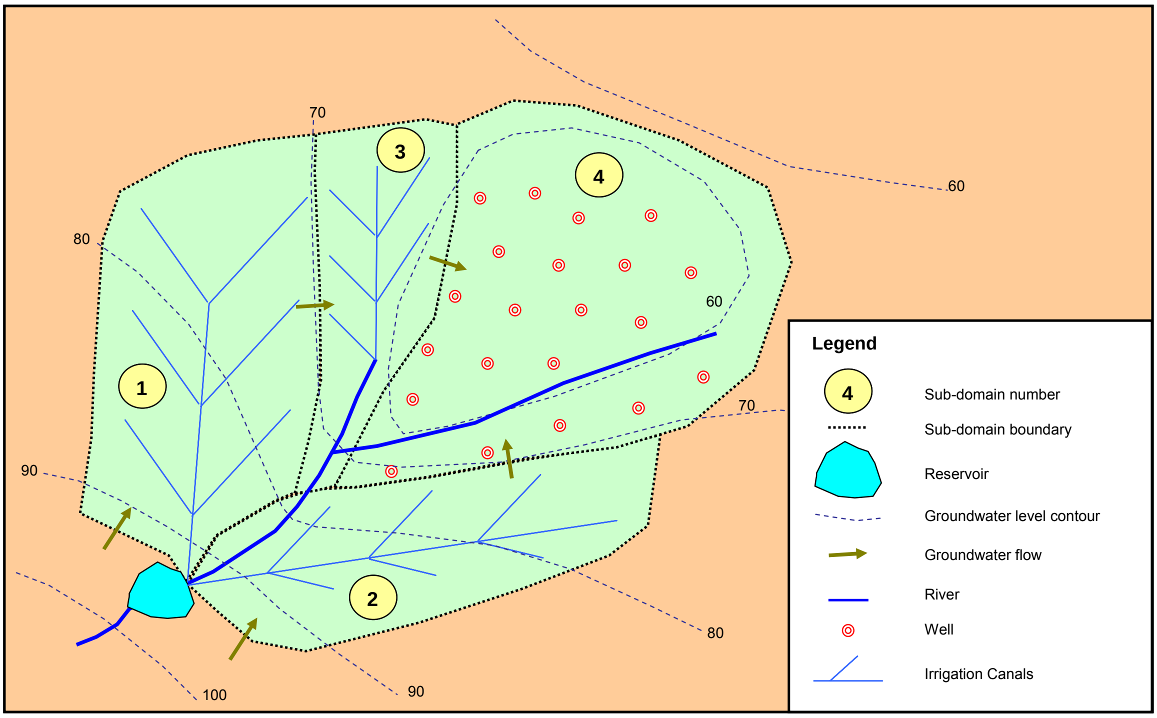
China – UK, WRDMAP
Integrated Water Resources Management Document Series

Thematic Paper 1.2: Groundwater Resource Quantity Assessment

May 2010



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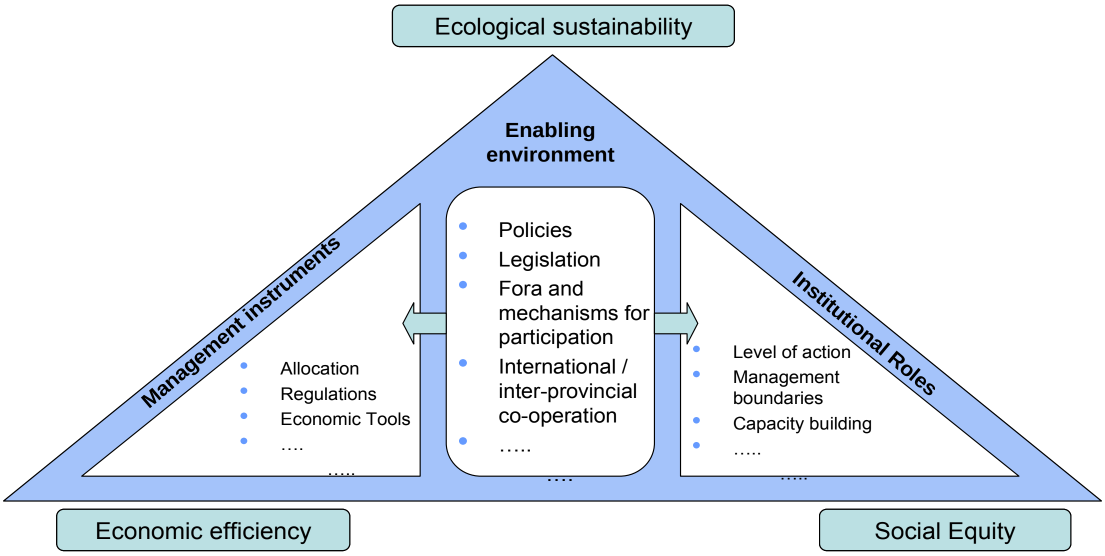
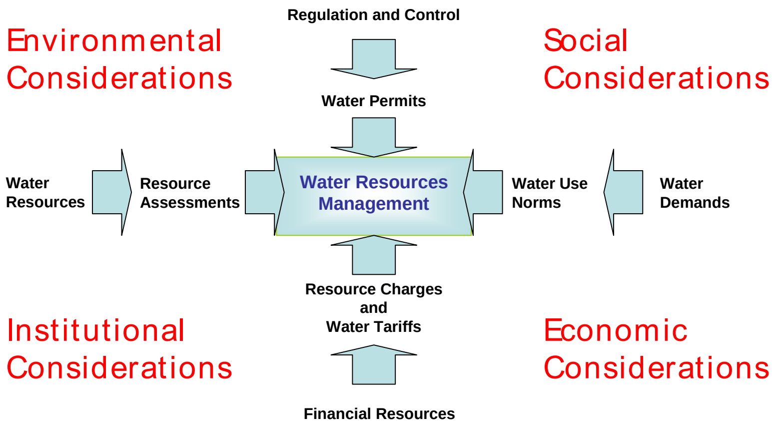
Integrated Water Resources Management (IWRM)

(Basics after Global Water Partnership)



Driving Elements of Integrated Water Resources Management



(Second figure after WRDMAP)

Summary: Groundwater resource quantity assessment approaches can range from very basic to highly complex. This paper provides guidance on the choice of an appropriate approach which will provide 'best value for money', and which allows for realistic expectation of the value of the approach. It promotes a rational and phased approach with basic approaches preceding more advanced ones.

The paper is one of a series of documents which aim to provide practical guidance to Water Resources Department / Water Affairs Bureau in dealing with integrated water resources management in their area.

This Thematic Paper comprises the following topics:

1. Introduction
2. Project scoping
3. Assessments methods of groundwater quantity (at 4 levels of complexity, from basic to advanced)
4. Procedures for calculation

This document is one of a series covering topics on sustainable water resources planning, allocation and management. Details are given in the bibliography.

The Ministry of Water Resources have supported the Water Resources Demand Management Assistance Project (WRDMAP) to develop this series to support WRD/WAB at provincial, municipal and county levels in their efforts to achieve sustainable water use.

1 Introduction

Groundwater resource assessment approaches can range from very basic to highly complex. This paper provides guidance on choosing the appropriate approach which provides *'best value for money'* and which allows for realistic expectation of the value of the approach.

With the advance of computer technology it is all too tempting to opt for very advanced assessment approaches without the backing of good data and capable staff resources. This paper promotes a rational and phased approach with basic approaches preceding more advanced ones and pointing to better understanding of data needs for such advanced approaches. The value of an advanced approach can be hugely limited by poor data and the term 'rubbish in, rubbish out', often used when referring to advanced groundwater models, is very relevant.

Groundwater resource assessment, particularly when related to regional and complex aquifer systems, is a long term process. It can take many years and requires continuous improvement through use of new data and improved resource simulation.

Understanding the dynamic behaviour of groundwater systems is important to allow for long-term sustainable use of available groundwater resources. Good understanding leads to improved planning and management of water allocation and use.

Important issues that may constrain effective use of groundwater management approaches and selection of the most appropriate ones include:

- Access to data and knowledge sharing
- Technical capability and availability of staff within resource management bureaux/institutions
- High expectation of advanced assessment approaches
- Lack of standardisation in approach

2 Project Scoping

It is recommended that a scoping study is undertaken before the phased development of groundwater assessment. It is the first step in getting activities started. It will normally form the basis for identifying the assessment approach.

The objectives and scale of a scoping study depend on a number of variables such as the size of the assessment work, the amount of work already carried out and the proposed approach to the main part of the project. The principal objectives are:

- To clarify and agree the overall purpose and define clear, specific objectives for the groundwater assessment
- To identify the main issues
- To identify the available data, where and in what format is it stored, its quality and its availability
- To identify critical gaps in the data and likely cost and timescale for obtaining this data (particularly for the more advanced assessment methods)
- To identify and review relevant previous investigations and research and its availability
- To define the likely geographical extent of the project area
- To summarise the current conceptual understanding of the project area and to identify any uncertainties
- If relevant, to identify technical issues that need to be addressed
- If relevant, to identify and contact key interested parties. Stakeholders may include interest groups such as for example farmers and industries, who rely on the use of groundwater for their livelihoods/business
- If relevant, to identify an appropriate and effective communication and participation strategy
- If relevant, to identify the benefits of the project in general and to stakeholders, and to develop an outline benefits realisation strategy.

Groundwater resource assessment approaches—Methods 1, 2, 3, and 4—vary from the very basic to the very complex (Table 1). Based on the project scoping described above, an assessment approach is determined based on necessary criteria (Tables 2 and 3) and using a decision tree (Figure 1). A project description, including a work plan, staffing, timing and budget is then prepared. For the very advanced assessment level (see Table 3), staff input from external and specialised organisations needs to be considered.

Sufficient and appropriate data is vital to successful completion of groundwater assessment. The data does is not limited to pure groundwater related data and is, particularly for the advanced assessment methods, much broader. Table 2 provides detail related to the following data categories:

- **Geology**: to enable characterisation of the groundwater system
- **Hydrogeology**: for the characterisation of groundwater system properties, particularly aquifer transmissivity and conductance of low-permeability layers (aquitards)
- **Hydrology**: to characterise the surface water system and its inter-relationship with the groundwater system
- **Soils**: to assist in the determination of recharge to groundwater
- **Land use**: also to assist in the recharge assessment
- **Irrigation**: the irrigation distribution system and the irrigation practices determine recharge to groundwater
- **Water use and distribution of water**: determines the output of water from groundwater (abstraction) and also recharge from potable water distribution

3 Assessment Methods

3.1 Introduction

The sustainable development of water resources requires appropriate strategies in respect of surface water allocation and groundwater abstraction management. Optimal and yet sustainable development of groundwater (without compromising environmental needs and groundwater quality) is a major challenge. It requires a comprehensive understanding of the dynamics of the groundwater system and its relationship with the surface water environment, and groundwater abstraction characteristics.

Tools available for groundwater resources assessment can vary considerably in complexity. They may range from simple lumped water balance equations to complex distributed groundwater models integrated with surface water systems. The first are cheap, but often very approximate and do not always allow for a good understanding of the dynamic nature of groundwater systems. The latter are expensive and data hungry and require considerable expertise at all stages of development.

Different groundwater resource assessment approaches—Methods 1, 2, 3, and 4—are outlined in detail in the following sections and are further elaborated in Tables 1 to 3 below. The benefits of using a gradual process of building understanding of groundwater resources and the development of assessment/management tools can be significant. The use of an initial assessment based on Methods 1 and 2 allows for better focus on the development of the more advanced methods, while it also provides clarity on data and staffing required for the more advanced assessment approaches. Such focus can result in considerable savings in time and money and sensitises senior management to the challenges of the process.

The most advanced assessment approach, which involves the use of complex integrated groundwater and surface water models, would thus be preceded by an initial and more approximate assessment, often part of a detailed scoping study.

Table 1: Groundwater assessment approaches

Approach	Scope and Objective	Assessment tools	Accuracy	Future Use
Method 1	Preliminary assessment based on limited data, which does not require advanced tools and specialists.	Mainly done without the need for complex assessment tools. Tools used on a day to day basis such as Excel may be used to store and manipulate data.	Approximate and limited by data, staff capability and time. Depends also on scope and objectives.	This method could be retained and used again. It can form the basis for more advanced assessment, when better data and/or more time and budget are available.
Method 2	A more advanced assessment, which can be re-used and could form a sound basis for more advanced assessment. Data integration and conceptualisation of the integrated surface water and groundwater system are important.	Advanced assessment tools such as Excel and data base programs are used in the processing and analysis of data. Basic assessment methodologies are used, including Excel based water balance analysis.	Better and sometimes good accuracy can be achieved with this method, largely dependent on the availability and quality of data, on available budget and staff experience.	Assessment procedures and tools can be usefully used for resource management and planning. Accuracy and precision of assessment depend on the degree of approximation in the representation of complex groundwater systems.
Method 3	An in-depth and comprehensive assessment using advanced analysis tools, including GIS, and specialist staff resources.	Excel, database programs and GIS are used in the processing of data, assessment of resource availability and processing of results from assessment tools. GIS is extensively used in data and results processing and visualisation. More advanced water balance analysis is done, using spreadsheet methods or stand-alone lumped water balance simulation models.	One should aim for high accuracy using this method and thus data availability needs to be good and staff experience advanced. This method enables assessment of uncertainty and provides guidance for additional field investigation and monitoring programs.	Tools developed using this method can be used and updated/improved when more data become available. This method should be seen as one that can be developed within the water resources management organisations, without requirement of external specialists/organisations. It may require appropriate training of staff and/or employment of relevant specialists.
Method 4	This method is the most advanced for resource assessment, planning and management. It allows for very detailed assessments and accurate representation of historical and future groundwater resource behaviour under both varying climatic and anthropogenic influences.	Advanced distributed numerical models linked with GIS systems are used in the detailed assessment of groundwater behaviour. Groundwater models need to be comprehensive and able to accurately represent surface water interactions. Groundwater modelling is often used in conjunction with surface water models. MIS systems can be used to integrate models with resource planning/ management tools.	Accuracy and definition of uncertainty are at a very high level and this allows for accurate prediction of future groundwater level behaviour in response to changing/ variable climatic and anthropogenic influences.	The tools developed under this level should be seen as long-term assessment tools, which are used on a regular basis for resources planning and management. They need to be updated and, if needed, re-calibrated on a regular basis when more data become available. The development of the tools should be seen as a long-term investment.

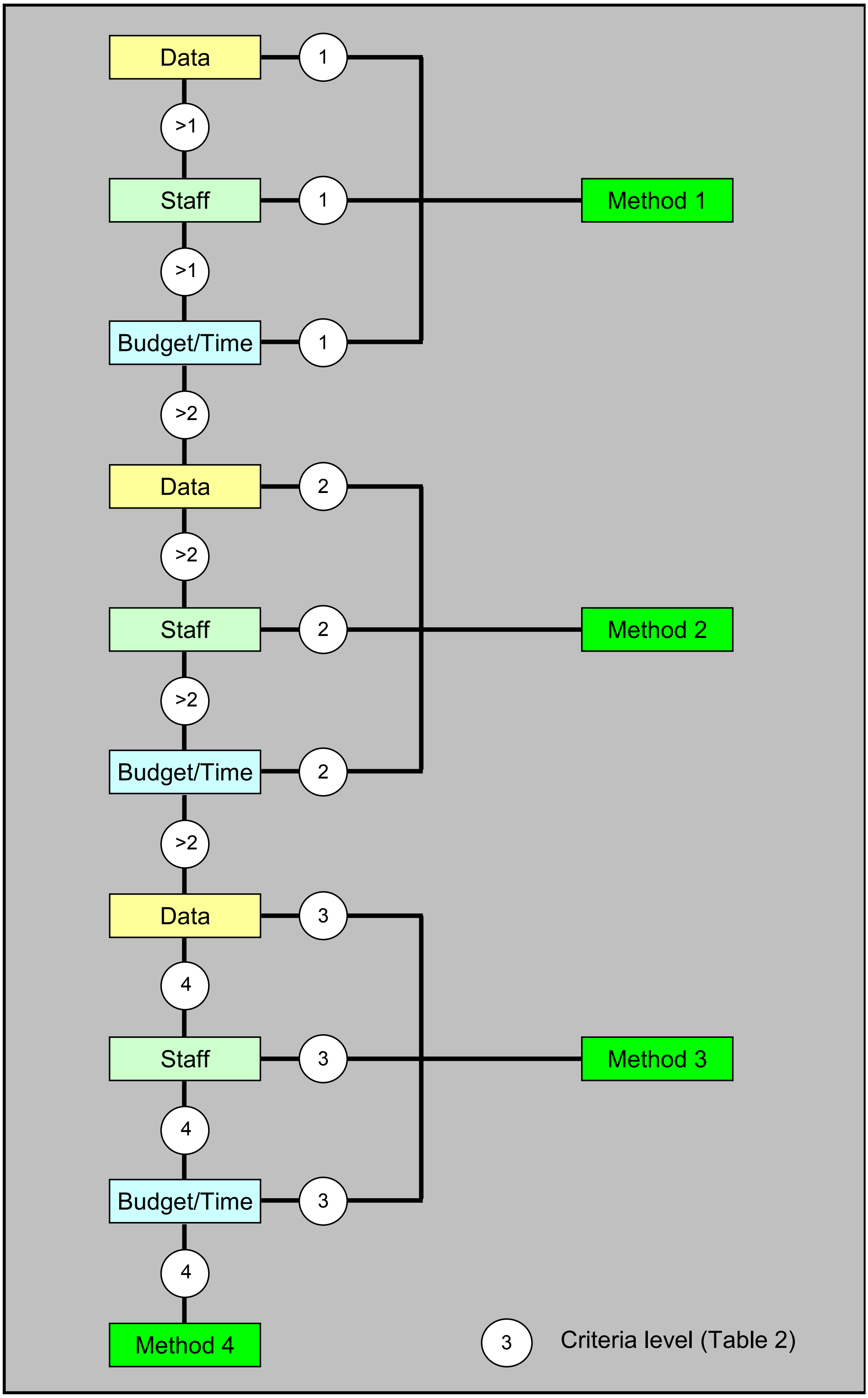
Table 2: Data requirements and availability for groundwater resource assessment

Data Category	**Groundwater Resource Assessment Method**		
	Basic (Method 1)	**Intermediate (Method 2)**	**Advanced and very advanced (Methods 3 and 4)**
Geology	A basic understanding of geology is required that allows for identification of aquifers and aquitards.	A better understanding of spatial variability in geology is required than for the basic case.	Detailed knowledge of geology is available from a variety of data sources, which allows for 3-dimensional mapping of geological formations
Hydrogeology	A basic understanding of the hydraulic characteristics of the groundwater system is available or based on knowledge of similar systems. Requires some knowledge of groundwater levels both in space and time.	Hydraulic characteristics are more precisely defined and rely in part on aquifer testing. Groundwater piezometry is spatially better defined and based on a more extensive monitoring network. Time variant data may not be too refined, but changes over longer time periods are defined.	The hydrogeological characterisation of the groundwater system is based on pumping test data and hydrogeological studies undertaken in the past. Extensive monitoring of groundwater levels and groundwater quality has been undertaken over a number of years and allows for detailed spatial and temporal characterisation of piezometry. Some understanding also exists on vertical hydraulic gradients in the groundwater system if this comprises multiple aquifers and aquitards.
Hydrology	Basic knowledge exists of rainfall and evaporation for the area under consideration based on long-term average or annual values. Also a basic understanding exists of the river system and how this relates to geology and its interaction with the groundwater system	A better understanding of spatial distribution of long-term average rainfall is available. There is also better understanding of time variance, which allows for assessment of annual, seasonal and monthly variations. The river system is better defined in terms of the relationship between river levels and groundwater levels, which allows for better definition of gains and losses.	Available climate data is such that both spatial and temporal variability in rainfall and evaporation can be obtained, down to small time periods as small as one day. Such data allows for accurate assessment of water requirements and recharge. The river system is well defined and river flow and river level measurements allow for more accurate evaluation of river gains and losses.
Soils	There is a basic understanding of soil properties, particularly their ability to allow recharge to the aquifer	Soil distribution and properties are better defined and allow some judgement on their capacity to store soil moisture and this allows for better assessment of groundwater recharge.	Soil data is extensively available and includes information on soil physical properties that allow for improved assessment of the moisture balances used in recharge assessment. The data also allows for calculation of capillary flux from a shallow water table.
Land Use	A basic knowledge exists of vegetation and crop distribution and also the extent of urban areas.	Land use is better defined spatially and over short and long time periods and this allows for a better assessment of historical trends in water requirements and use.	Detailed information on land use allows for spatial and temporal distribution of land use data.
Irrigated Agriculture	Basic knowledge of irrigation requirements and water use from surface water and groundwater sources is available. Some knowledge of the spatial distribution of water use, based on land use and water requirements is also available.	Water requirements are better defined from historical data on land use, better knowledge of water distribution in irrigation systems and use of groundwater for irrigation. Thus the spatial and time variant nature of water requirements is better understood.	Water requirements can be calculated using climate and land use data and can be verified from monitored water use. The spatial and time variant nature of water requirements can thus be defined more accurately.
Water Use and Distribution	A quantitative knowledge of water use, including groundwater abstraction and surface water use is available. In urban/industrial areas there needs to be knowledge of total water use and also about leakage to the underlying groundwater.	Water use can be better defined both spatially and in terms of time and this relates to both surface water and groundwater. Urban water use can also be better defined from better historical water use data.	A good understanding exists of water use for different purposes, both in terms of spatial distribution and variation with time. Detailed information is available for both surface water and groundwater use. Where gaps in data coverage exist, available data allow for interpolation or indirect determination of water use.

Table 3: Criteria related to groundwater resource assessment and planning/management

Criteria	Method 1	Method 2	Method 3	Method 4
	Basic	**Intermediate**	**Advanced**	**Very Advanced**
Staff expertise	Basic hydrogeological, hydrological and water use knowledge/ skills are required.	Experienced hydrogeologists, hydrologists, and water use experts are required. Expertise includes the use of more advanced computer facilities such as Excel and database tools.	Experienced hydrogeologists, hydrologists, water use and GIS specialists are required. Expertise includes the use of more advanced assessment tools.	This method requires a very high level of expertise, not always available within the management bureaux. It often requires input from specialist organisations, particularly when complex distributed modelling is involved.
Budget/Cost	Low	Medium	Medium to high	High
Data	Limited data are available or data access is seriously constrained.	Existing knowledge is available from studies undertaken in the past, while data availability allows for assessment of spatial and time variant assessment of the groundwater resource. Data allow for analysis that captures spatial and time variant aspects.	Existing knowledge is available from studies undertaken in the past, while data availability allows for detailed assessment of spatial and time variant assessment of the groundwater resource. Data allow for in-depth analysis of spatial and time variant data.	Extensive knowledge and data are available to define the groundwater system in terms of its spatial and time variant characteristics. Data are of good quality and allow for accurate representation of the integrated surface water and groundwater system in advanced modelling tools.
Time available	A few months	Three to six months	Six months to one year	One to three years

Figure 1: Decision tree for determination of assessment method



The choice of method should be determined by the requirements of the assessment. Although tempting when budget, time and experienced staff are available, there is no real benefit in undertaking Methods 3 or 4 if data availability and data quality are limited. Although the tools will allow for detailed assessment of groundwater level components, both spatially and with time, the accuracy could be very limited because of all the data uncertainties. In that case it is not inconceivable that a basic method (Methods 1 or 2) would have provided answers of equal accuracy, resulting in time and money savings until data improvements have been achieved.

The description of the advanced Method 4 will indicate that the assessment process follows stages that include approaches described for the more basic assessment methods.

3.2 Basic concepts

For a detailed appreciation of groundwater and related issues, reference should be made to the relevant literature. The basic concepts described in the following merely aims at providing groundwater resource managers with some practical guidance related to the assessment approaches described in the following sections. GW•MATE Briefing Note 2 provides a useful introduction to the characterisation of groundwater systems, while the other briefing notes provide further detail.

Aquifer systems can range from simple, homogeneous and single layer aquifers to highly complex, heterogeneous and multi-layered systems of aquifers and aquitards. The extent of aquifer systems can also be variable and range from small areas (for example with shallow alluvial deposits in river valleys) to aquifers of major extent and sometimes covering more than one country (for example the Nubian Sandstone Aquifer in northern Africa).

Aquifers may thus be categorised as minor or major depending on their extent and also on their ability to yield groundwater using abstraction wells. They can also be categorised in terms of their geological history and hydrogeological characteristics. For example, unconsolidated alluvial aquifers are distinctly different from consolidated and often fractured aquifers.

The scope for simplification of complex multi-layer aquifer system, particularly when less advanced groundwater assessment methods are used, depends on the connectivity between individual aquifer layers. If the aquitards that separate aquifer layers have relatively high vertical hydraulic conductivity, then the development of vertical hydraulic gradients will be minor and the multi-layer aquifer system could be considered as a single unit.

Appendices A and B provide some simple guidance to the characterisation of aquifers and also provide some ranges of values for hydrogeological parameters used in groundwater assessment calculations. The parameter values only serve as likely estimates and there is a need for careful consideration of local conditions before parameter choices are made.

3.3 Method 1 – Basic/ preliminary approach

The assessment would be on a county or district level.

An initial assessment using a simple approach (Method 1) is undertaken for a variety of reasons:

- Constraints on data availability do not justify the use of more advanced methods, in which case the assessment is approximate and subject to uncertainty.
- When data are available, but constraints on staffing and/or budget/time exist, the assessment is undertaken to obtain a preliminary understanding of the groundwater system, which will lead to a better understanding of the requirements for more detailed assessments. In this case, although still approximate, the assessment will be more accurate.
- For this type of assessment there still needs to be some knowledge of geology and hydrogeology. This may be available for the area being assessed or understanding could be based on groundwater systems that are similar to the area under study. In nearly all cases there is prior knowledge about geology and hydrogeology even if this is on a regional scale (for example the hydrogeological atlas of China).

The extent of the assessment area is generally limited and could comprise a county or part thereof. Local knowledge on water use and allocation will be available and some knowledge on rainfall and its distribution are also available, although spatial and temporal distribution may be limited.

Resource availability is based on an estimation of recharge and on a basic assessment of groundwater inflows and outflows. Recharge is calculated as the sum of rainfall recharge and irrigation returns to groundwater (from both surface water and groundwater sources). Such calculations involve simple factoring of rainfall and irrigation water allocation. Groundwater inflows are based on groundwater gradients (if available) and aquifer properties (these may be estimates). If urban areas are significant, account needs to be taken of urban recharge, simply as a percentage of gross water supply. If rivers are of significance, groundwater gains may occur and this needs consideration in assessing contribution of river water to the aquifer.

Recharge components described above are compared with groundwater discharge, which includes groundwater abstraction for irrigation and urban water supply, groundwater outflows and groundwater inflow to rivers.

A simple water balance using annual or long-term average values for the components described above is prepared and allows for initial insight into the availability of groundwater and/or the level of stress already imposed on the groundwater system. Some knowledge of groundwater level changes may be available from monitoring and would allow for estimation of groundwater storage change. Time steps of one year duration would be sufficient to capture the long term dynamic behaviour of the aquifer system, for example when groundwater level decline has occurred over a number of decades. Some understanding of seasonal variability on resource behaviour needs to be considered and will depend on available groundwater level monitoring data.

There is likely to be a large degree of uncertainty in the simple approach, stemming from data limitations and from the simplification of the assessment of the inflow and outflow components of the groundwater balance. Uncertainty exists also with regards the time variant nature of the groundwater system and the water balance. Caution is thus required when this method is used for groundwater resources planning and management.

However, it can be a useful and cost-effective first step in groundwater resource assessment and can provide direction for undertaking field investigations and monitoring or enhance existing monitoring systems. It can be the first step in the process of developing better understanding of the groundwater system and its relationship with the surface environment, and lead to the development of improved resource assessment, planning and management tools. The approach will almost always help in identifying data difficulties and inaccuracies and should result in improvement in both monitoring networks and data quality.

The assessment can easily be undertaken by staff from local water affairs bureaux and does not require advanced computer facilities. Computer facilities used on a day to day basis, such as for example Excel, could be used in the assessment, but would not limit the use of Method 1.

3.4 Method 2 – Intermediate approach

This method is used when good data are available to define the groundwater system with a better degree of precision, although detail on spatial and/or temporal variation in data may still be limited. This method does not involve the use of numerical models, or the use of GIS. It does, however, use the more advanced facilities available in Excel and could also make use of a computerised database.

Groundwater resource assessment is based on a lumped water balance approach with the project area sub-divided into water balance sub-areas. This approach also takes consideration of time variance and will thus allow for representation of water balance variations over a historical period. The time step duration can be annual, seasonal or monthly. Shorter time steps would be possible, but place considerable demand on data processing and storage. Generally, monthly time steps are appropriate to allow for sufficiently detailed analysis.

A lumped water balance tool, developed in Excel, will be sufficiently detailed and accurate to be used as a planning and management tool. The limitations in its use as an assessment and prediction tool should, however, be recognised. Uncertainty relates to data and to the adequacy of representing spatial variability using a lumped approach.

Method 2 requires staff with good hydrogeological knowledge and good understanding of the local water use situation. Staff also need advanced knowledge of Excel and, if relevant, of database tools.

Meaningful assessment using Method 2 requires data as indicated in Table 2. Conceptual modelling is an important component of this method. A conceptual model is not a numerical model. It is a detailed expression of understanding of the behaviour of the groundwater system and its interaction with the surface environment. This understanding is developed using the conceptual modelling tasks described below. The development of the conceptual model starts from an initial understanding determined as part of the Scoping Study. The understanding is enhanced through an evolving and often iterative process until an agreed final conceptual model has been developed.

Data integration

Data integration is the first task in the model conceptualisation. It is a very important and often under-rated task. Data integration includes the interpretation of all data with particular emphasis on data inter-dependencies. Inter-dependencies include, for example, the dependency of groundwater levels on geology, hydrogeological characterisation of the aquifer system, irrigation and groundwater abstraction. The data integration allows for judgement of adequacy of data coverage and accuracy and will no doubt lead to better appreciation of the need for improved data and monitoring networks.

Recharge simulation

Recharge includes components such as deep percolation of rainfall surplus, seepage losses from irrigation canals, deep percolation from irrigation application at field level and leakage losses from urban water supply and sewage systems. For the Method 2 assessment, recharge would be based on factoring rainfall, canal flows, irrigation water applied at field level and gross water supply quantities to urban areas. Factors for rainfall may include a threshold rainfall value and a factor. For canal losses canal efficiency factors are used, which depend on the type of canal (lined or unlined). Deep percolation from irrigation at field level is based on a field efficiency factor. Urban recharge is determined by applying a factor to gross supply (largely determined from percentage leakage loss from the distribution system). In arid regions recharge from rainfall is often very limited and is therefore often ignored.

Preliminary water balances

Water balances are calculated for sub-areas of the project area (refer to Appendix A). The derivation of water balances focuses attention on the adequateness of the data sources, both in terms of spatial and temporal distribution as well as their degree of accuracy. Quantification of water balance components and the links of data to individual water balance components allows for judgement of significance of data components and hence the significance of lack of accuracy in data definition.

Uncertainty analysis

Uncertainty analysis is also an important task during conceptualisation. Uncertainty can be both spatially and time variant and its significance should be seen in terms of the influence of different data sets and parameter assumptions on water balance components. This initial analysis of uncertainty and an expression in quantitative terms will provide additional focus to further data collection and future refinement of the water balance.

Conceptual model

The tasks described above allow for the development of a thorough conceptual understanding of the groundwater system and its interaction with the surface environment. This conceptual understanding forms the basis for possible future implementation of a more advanced groundwater resource assessment.

The water balance would be calculated in an Excel spreadsheet, which also includes all the relevant data. The spreadsheet can be used as a planning and management tool to obtain estimates of groundwater behaviour under varying climatic and anthropogenic influences. The limitation of a lumped approach should be recognised. The spreadsheet tool will not be able to represent the complex dynamics of interaction between different water balance components. Limitations need to be taken into consideration when planning and management decisions are based on the output of such a tool. Judgement needs to be used and this requires involvement of experienced staff. As such models are built, it is often realised that an increasing number of assumptions are being made related to model parameters and concepts. The modelling can thus be continuously improved by researching these assumptions and concepts and thus improving their accuracy.

Figure 2 blow shows an example of the layout of a lumped water balance model. The example is one where surface water components to the groundwater system are user specified, which means that surface water components are not an integral component in the water balance approach. Components of the groundwater balance include:

- Recharge derived from rainfall, irrigation and leakage from urban water supply systems (if relevant)
- Seepage from rivers to groundwater and losses from groundwater to rivers (depending on groundwater levels relative to river levels)
- Groundwater abstraction
- Groundwater flow across sub-areas
- Groundwater storage change (if relevant)

One would aim to achieve a closing balance for each sub-area of the model and for the whole model as well.

3.5 Method 3 – Advanced approach

Method 3 would make extensive use of GIS for data processing and for visualisation of spatial data and water balance simulation results. The water balance approach would also be more advanced and would generally include more refined division of the project area into sub-areas and use of monthly time steps.

The assessment approach in Method 3 is advanced. Tools that are developed should be considered for enhanced planning and management of groundwater resources. The implementation of this approach and the development of relevant tools require good data, experienced staff in different disciplines and appropriate budget and time.

Budget and time requirements will depend on previous resource assessments and would be less if Methods 1 or 2 has been used previously. If not, Method 3 would follow a staged process with components of Methods 1 and 2 comprising important stages in its implementation. Components of Method 1 would be used in the Scoping Stage, while the conceptualisation would follow the approach described for Method 2.

The water balance can, as for Method 2, be simulated in an Excel spreadsheet, but is more generally done using a stand-alone lumped groundwater balance model that is linked to a GIS or operated within a GIS environment.

The conceptual model development includes the same tasks as described for Method 2. The tasks are undertaken in more detail and with more precision. Use is made of observation data so that some of the water balance components can be made to match with direct measurements. This represents a simple and approximate calibration process not normally used in Method 2. The calibration allows for improved accuracy of the water balance tool in groundwater resource planning and management and also for better appreciation of uncertainty.

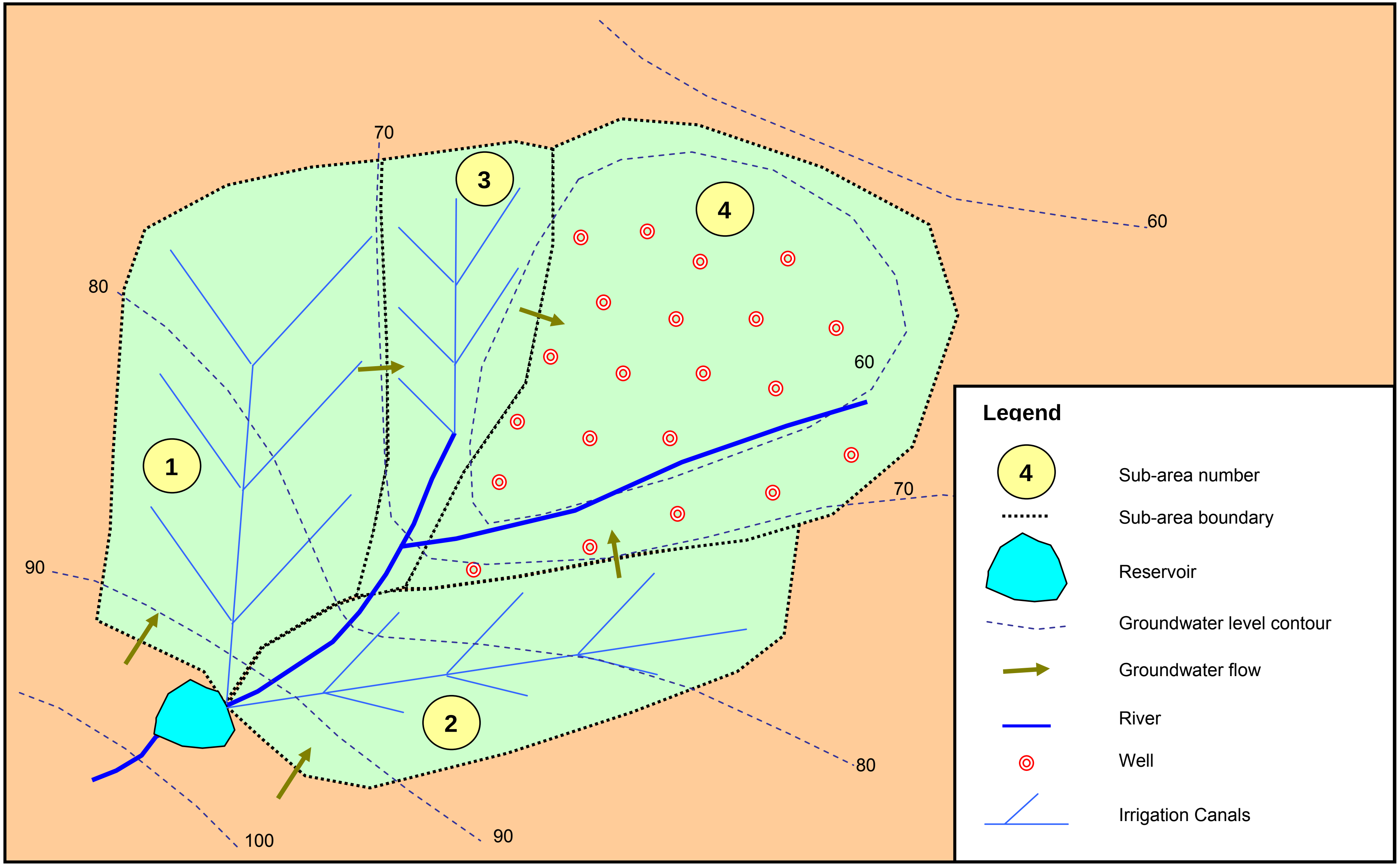
The example of the sub-division of the water balance area into sub-areas as shown in Figure 2 would still apply, although more refinement may be required. The difference with Method 2 is that the dynamics of the surface water/groundwater inter-relationships are build into the model. Thus the model could include a reservoir module, an irrigation module, a river module, a drainage module, an urban recharge module, etc. The water balance thus integrates both surface water and groundwater components. For the water balance example shown in Figure 2, the modules and water balance components described in the following would be used.

Groundwater components would be the same as for Method 2 although the derivation of some components would be linked to the surface water modules. Recharge is thus based on calculations done in the irrigation module and in the river module, while taking consideration of the contribution from rainfall on recharge.

The surface water components and their links with the groundwater system can in summary be dealt with as follows:

- A river module would divide the river system up into reaches and the choice of reaches is preferably related to the physical characteristics of the river system and the availability of gauging data. Losses and gains related to the river/aquifer exchange would be determined in the module by taking account of the dynamics of the river system. Thus upstream inflows, downstream outflows, diversions, discharges (for example from sewage treatment works or storm runoff systems), evaporation and river/aquifer exchange would form components of the river balance. When data are available on some of the components, the calculated river/aquifer interactions can be verified.
- An irrigation module incorporates all the components of an irrigation balance and aims at determining, with more precision, the recharge to the underlying groundwater system. The model incorporates inflows from surface water, groundwater application (if relevant), distribution system efficiency, field irrigation efficiency (with possible distinction between irrigation from surface water and from groundwater), crop water requirements and outflow from the model or to adjacent sub-areas and possible outflow to drainage systems (if relevant). Account would be taken of the non-beneficial losses, which are often determined as a percentage of total irrigation losses.

Figure 2: Example of lumped water balance model components for Method 2



- A drainage module would be relevant in areas where shallow groundwater table conditions occur. Inflows to the drainage system derive from surplus irrigation water (tail end outflows) and from groundwater when the groundwater table rises above drain level. In general, groundwater levels are related to groundwater storage, which is calculated in the groundwater module. Drainage outflow then follows from relationships with groundwater storage. If drainage outflow measurements are available, such relationships can be derived with a reasonable degree of precision.
- A reservoir module would allow for inclusion of the dynamics of reservoir operation and releases of water for irrigation.
- An urban recharge and discharge module would include relationships between water supply and leakage to groundwater. It would also include the calculation of storm water runoff and sewage outflow, which could both become inflows to the river system.
- Most lumped water balance models are used for surface water irrigation planning and management and mostly have a weakly defined groundwater module. The WEAP model, which is used for planning and management in the Shiyang River Basin in Gansu Province, is an example. Careful consideration therefore needs to be given to the relative importance of the water balance modules (to overcome the limitations in the WEAP model, it has been linked to a distributed groundwater model developed by Tsinghua University). If the main focus is on groundwater resource planning and management, then the groundwater module needs to be robust and sufficiently refined to accommodate both spatial and time variant aspects.

The GIS will play an important part in the Method 3 approach. It is used for spatial analysis and the visualisation of spatial characteristics of the groundwater system and the related surface aspects. It is also used to visualise the results of the water balance model and could be used as the platform for operation of the model, including the specification and manipulation of data. Other computer facilities, in particular Excel, may be more suitable to process and visualise the time variant components.

In the Method 3 approach, more reliance is placed on monitoring data, related to the groundwater and surface water systems. Such data would be used in model calibration, in determining relationships between surface water and groundwater systems and the groundwater exchange between sub-areas. If groundwater level data are available, then changes over time can be related to inflow and outflow components, such as recharge, groundwater abstraction and river/aquifer exchange.

The water balance is expressed for each unit and for the water balance area as a whole as follows:

$$RECH + QRIV - ABSTR - QFLUX + \Sigma QLAT + \Delta STOR = 0$$

where

RECH	-	recharge total for the assessment period
QRIV	-	contributions from rivers (+) or groundwater flow to rivers (-)
ABSTR	-	gross abstraction total for the assessment period
QFLUX	-	evaporation from a shallow groundwater table (in areas within the catchment where this is relevant)
ΣQLAT	-	sum of lateral groundwater flow across area or sub-area boundary for the assessment period (inflow is positive, outflow negative)
ΔSTOR	-	change in groundwater storage for the assessment period (positive for falling groundwater levels)

Due to uncertainties in the quantification of water balance components, it is unlikely that a balance will be achieved. Adjustments will need to be made to components until a balance is achieved. This is done through a simple calibration process, by changing the parameters that control the magnitude of individual water balance components. Table 4 provides guidance on this. It is possible that feedback to a surface water balance model is required when changes to recharge are believed necessary.

Table 4 Relationship between Water Balance Components and Controlling Parameters

Water Balance Component	Parameters
Recharge	• Rainfall • Soil classification and parameters (to assess soil moisture balance of the root zone) • Evapotranspiration • Data from reports, climate stations and modelling studies • Gross potable supply to urban areas • "Return flow" factor (factor defining proportion of gross supply returning to groundwater) • Gross irrigation supply and canal flows • Irrigation efficiency factors including field application and distribution efficiencies Data could be directly derived from a surface water model such as the WEAP model, and if modification to recharge is required, then such a model needs to be adjusted.
Groundwater abstraction	• Actual abstraction for irrigation, industry and domestic use
Evaporation groundwater table	• Depth to the groundwater table • Soil physical parameters that determine the relationship between shallow water table evaporation and the depth to the groundwater table
Lateral groundwater flow	• Groundwater levels • Transmissivity
Storage change	• Storage coefficient • Groundwater levels

3.6 Method 4 – Very advanced approach

The Method 4 approach is much more advanced than Method 3 and includes the use of distributed and interlinked groundwater and surface water models. Such models, linked to advanced GIS systems are used for detailed planning and management of groundwater resources.

This method requires extensive data and a high degree of completeness and accuracy of data sets (refer to Table 2). Data availability and quality needs to be such that spatial variability can be well defined and that time variant behaviour can be understood over a sufficiently long time period.

The accuracy of models depends to a large degree on data availability and quality for model calibration, on expertise and experience of modellers, and on available time and budget (refer to Tables 2 and 3). Considerable investment is required to develop the modelling tools and the pre- and post-processing environment, such as GIS. Such investment would be largely wasted if the criteria set out in Table 3 are not satisfied. Good monitoring data is essential to the successful implementation of this method. Monitoring items need to be comprehensive as listed in Table 5.

Method 4 follows a staged approach and for integrated groundwater and surface water modelling this is described in Thematic Paper 1.1 'Groundwater Flow Modelling'. This paper describes modelling as a process and not simply a computer application. The process includes a number of important components, which include aspects described for the less advanced assessment methods.

There are considerable advantages of using complex distributed models:

- Aquifer systems are spatially variable and dynamic in their response to time-variant influences such as climate and human interventions (such as for example groundwater abstraction and use of river water for irrigation). Distributed numerical models allow for inclusion of both spatial and temporal variability and can thus most accurately represent the real aquifer system.
- A pre-requisite for the development of distributed groundwater models is an in-depth assessment of all available data and knowledge, and the development of a comprehensive conceptual understanding of the behaviour of the groundwater system, both in space and time.
- If used appropriately, distributed models allow for a systematic assessment of uncertainty and thus allow for more focused programmes of field investigations and monitoring aimed at reducing uncertainty. Understanding uncertainty will also lead to a better appreciation of the reliability of model predictions.
- The models, although costly in developing, can reap substantial benefits through:
  - Rapid assessment of a large number of potential future resource development and management options.
  - Risk minimisation, particularly when the models have been adequately calibrated and are based on a sound and comprehensive database and conceptual understanding of the groundwater system.
  - The model can contribute to activities related to water resources and environmental drivers. For example, it could be used in the assessment of permit requests in relation to resource availability, or to assess the environmental impact of resource management alternatives.
  - When used as a tool to evaluate the need for field and monitoring data, it can result in considerable savings of time and cost related to field investigation and monitoring programs.
  - The model can also be used as a tool for conflict resolution in relation to water resource or environmental issues and may thus avoid the need for costly litigation (as is the case in many other countries).
- A complex model can greatly enhance the understanding of groundwater level behaviour and can result in improvement of simpler models (Method 3) with which personnel from local water management bureaus are familiar and use on a regular basis. This would thus result in continuous improvement of such models and in improved management practice at the local level.

Table 5: Monitoring requirements for groundwater assessment

Water balance/ resource component		Data requirements (monitoring data shown in bold)
Lateral flow across aquifer boundaries		• Elevations on base of layers • **Groundwater levels for layers** (spatial and temporal distribution) • Aquifer transmissivity
Leakage flows between aquifers		• Thickness of layers • **Groundwater levels for layers** (spatial and temporal distribution) • Vertical permeability
Storage changes		• Storage coefficients (unconfined & confined) • Groundwater levels for layers (spatial and temporal distribution)
Recharge	Natural (rainfall)	• Mapping of non-irrigated areas • Spatial and temporal distribution of rainfall • Soil classification and parameters (to assess soil moisture balance of root zone) • Evapotranspiration • Data from reports, climate stations and modelling studies
	Urban	• Gross potable supply to urban areas • "Return flow" factor (factor defining proportion of gross supply returning to groundwater)
	Irrigation	• **Gross irrigation supply and canal flows** • Irrigated areas • Irrigation efficiency factors including field application and distribution efficiencies
Surface water – ground water interaction	River/canal aquifer interaction	• **Groundwater levels** • **River levels** (together with groundwater this enables determination of surface water and groundwater interaction). • **River flows** at key gauging points • **Diversions** (together with river flows this enables carrying out a water balance for river reaches and determining whether the river is "gaining" or "loosing" water from/to the aquifer) • River surface area (could be time variant) • River bed conductance (together with river surface area enables estimation of possible seepage to the aquifer using analytical techniques)
	Reservoir aquifer interaction	• **Reservoir levels** • Surface water area (often directly related to reservoir level) • **Groundwater levels**
Discharge	Abstraction	• Well permit records • History of number and types of well • Average daily abstraction for irrigation, industry and domestic use • Irrigated areas, cropping calendar, crop demands, crop quotas and irrigation efficiency
	Capillary losses (only in shallow water table areas)	• Ground surface elevations • Soil types and their physical parameters • Rooting depths for various crops • **Groundwater levels**
Groundwater and Surface Water Salinity		• **Historical groundwater salinity data** • **Salinity of recharge components** • **Salinity of abstracted groundwater**

There is, however, a need for caution when deciding on the costly route of distributed model development. In particular:

- The phrase ‘a model is only as accurate as the data that feeds it’ holds true in many cases. It is essential to realise that the accuracy of a model relies heavily on the availability of a comprehensive database and availability of this database to the model developers.
- The development of a good model requires on the one hand a high degree of specialisation in hydrogeology and numerical modelling. On the other hand, it requires transparency in the development process and involvement of stakeholders throughout the model development process is equally important. In this context, the phrase ‘professional knowledge contributes to making parametric assumptions’ is equally relevant.
- The need for high levels of expertise required for the development and operation of highly complex models often results in the inability of the local water resource management personnel to use/operate the model. This factor should be an aspect of the original ‘choice’ of approach. Furthermore, the need for use of a complex model by local personnel should encourage the development of user-friendly model operating and pre- and post-processing facilities.

The model development should not be a one-off exercise, rather should be seen as the start of a process of continued resource evaluation, which will result in a gradual strengthening of the model as a resource management tool. The cyclical process of groundwater modelling is illustrated in Figure 3. The duration of a model cycle can be variable, but normally ends when need for re-calibration of the historical model is required. As a rule of thumb, the duration of a modelling cycle would be 3 to 5 years.

4 Calculation Procedures

4.1 Recharge from rainfall for non-irrigated areas

For Methods 1 and 2, recharge can be calculated as follows:

$$Rainrech = (Rain - T_{rain}) * RF$$

where

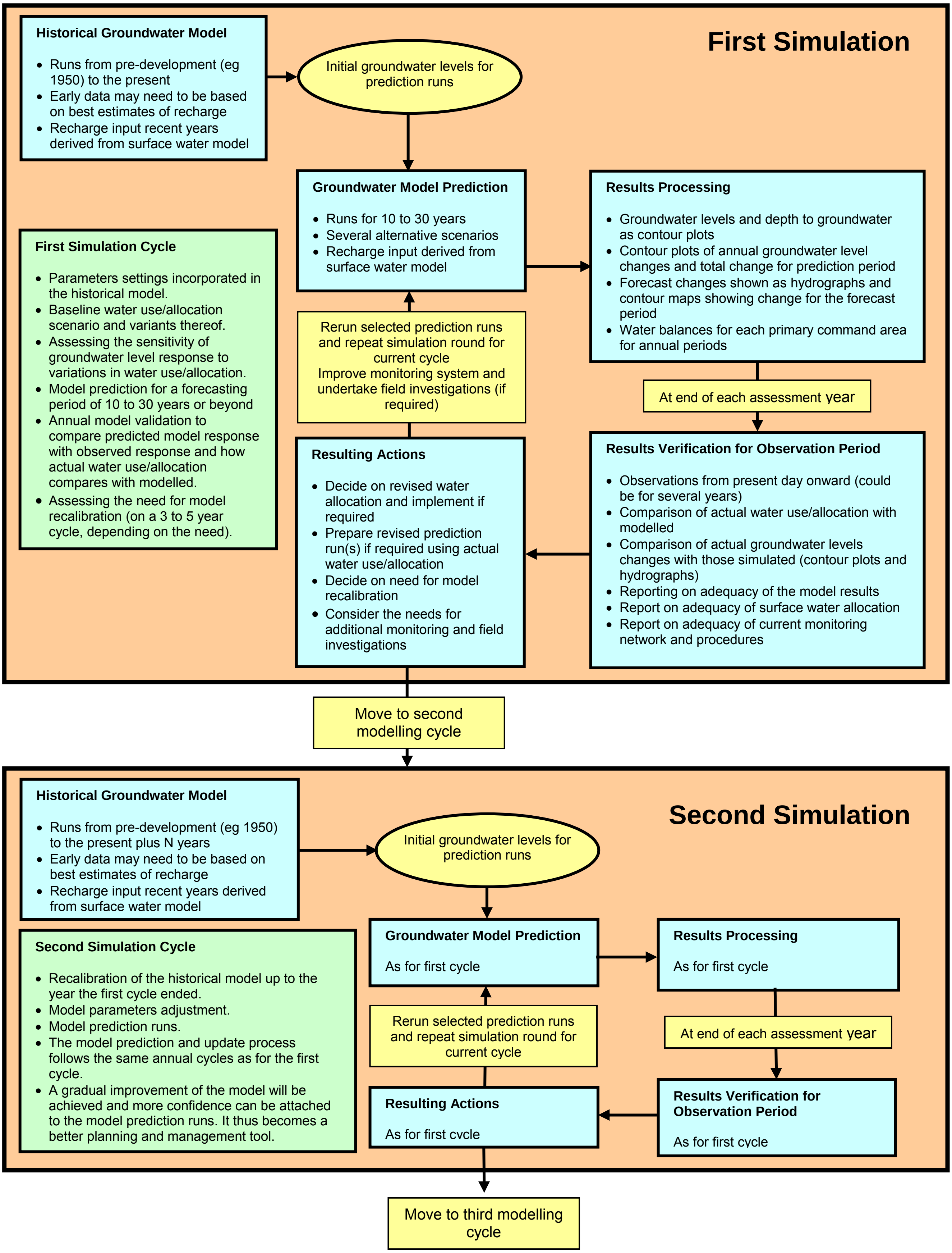
Rain - total rainfall for a specified time period (a time step) or long-term average recharge

T_{rain} - threshold value for rainfall (if rainfall is less then this value, recharge will be zero)

RF - rainfall factor (<1)

For Methods 3 and 4 more advanced and time variant methods are used, which involve the calculation of surface runoff, interception by vegetation, soil infiltration and a soil moisture balance in the root zone. Recharge will occur when soil moisture in the root zone rises above field capacity. A percentage of the infiltration through the soil surface may contribute directly to recharge and thus bypass the soil moisture process in the root zone (referred to as rapid recharge). Time steps could be as small as one day.

Figure 3: Model simulation cycles



4.2 Recharge from irrigation

Recharge includes a percentage of seepage loss from irrigation canals and a percentage of field loss from field scale water distribution and application. Generally recharge is based on canal flow and a canal efficiency factor, and on water supply at field level and field application efficiency. Not all loss contributes to groundwater; some losses are non-beneficial, generally in the form of evaporation.

Canal losses are generally based on a percentage of inflow into a canal system. In reality the loss will be a function of residence time of water in the canal, the conductance of the canal wetted perimeter and canal length, with the conductance dependent on the status of the canal (unlined or lined, and quality of lining). For canal efficiency in the range of 60 to 80%, the losses from canals are a significant contributor to total recharge. Accuracy in the estimation of canal efficiency is therefore required and derivation using flow measurements is recommended. Some of the canal losses are non-beneficial and include evaporation from the water surface and evaporation of residual water when the canal is not in continuous use. These losses are small for lined canals, while residual losses for unlined canals may be higher (due to evaporation of soil moisture contained in the canal bed). Quantification of such losses is required.

Recharge from water distribution and application at field level can be done by applying field application efficiency factors and application based on irrigation norms (see Advisory Note 1.8/2 ‘Agricultural Water Use Norms’). Efficiency can vary depending on the source of water (surface water will have more extensive field scale distribution) and on irrigation techniques (higher efficiency is for example achieved with drip irrigation compared with furrow irrigation). In the selection of field efficiency factors, one needs to consider the irrigation technique and differentiate between leaching (autumn and/or early spring applications) and crop irrigation periods (which determine both type of water application and depth of water applied). Leaching is normally done by flooding fields (which implies a lower field application efficiency) while higher field efficiency applies during crop irrigation when furrow irrigation is generally used and irrigation applications are small. Recharge that originates from field application of irrigation water forms an important component of aquifer recharge. For irrigation using groundwater, field efficiency is normally higher and this is attributed to more limited water distribution requirements at field level. The calculation procedure is as follows and relates to a canal command area:

For canal distribution losses:

$$QC_{loss} = QC_{flow} * (1 - eff_c)$$

$$QC_{rech} = QC_{loss} * (1 - fac_{nb})$$

where

- QC_{loss} - total loss from canal system
- QC_{flow} - canal flow at entry to command area
- eff_c - canal efficiency
- QC_{rech} - canal loss contribution to groundwater
- fac_{nb} - non-beneficial loss factor for canal system

For field application losses:

$$QF_{loss} = (QC_{flow} – QC_{loss}) * (1 – eff_f)$$

$$QF_{rech} = QF_{loss} * (1 – faf_{nb})$$

where

QF_{loss} - total loss from field application system (including field canals)

QF_{flow} - canal flow at entry to fields

Eff_f - field efficiency

QF_{rech} - field loss contribution to groundwater

faf_{nb} - non-beneficial loss factor for field system

Total recharge is thus determined from:

$$QT_{rech} = QC_{rech} – QF_{rech})$$

These formulae can be used in lumped parameter approaches as used in Methods 2 and 3. It can also be done on a distributed basis in Method 4. Recharge calculation could be more advanced in Method 4 by using a soil moisture balance analysis. This requires much shorter time periods (generally less than 10 and down to one day) and a very extensive data base, including information on rooting depths (as a time variant parameter) and soil moisture characteristics. Such methods are not described in this paper.

4.3 Urban recharge

Urban recharge can originate from three sources:

1. Rainfall or irrigation on non-build up areas (gardens, parks, road verges, etc)
2. Storm water drainage and sewage networks
3. Water supply systems

The first component would use calculation procedures similar to those used for rainfall recharge and/or recharge originating from amenity and garden irrigation. Data requirements would be as described above and also include the percentage of urban area not built on.

The second component is generally difficult to determine without the use of storm water drainage models. In arid areas where rainfall runoff is generally small, the calculation can be based on total water supply, a supply to foul drainage conversion factor and a leakage factor. Such factors are not easily determined.

The third component is probably the major contribution to urban recharge in arid regions. It is in its simplest way calculated as a percentage of total water supplies. Values can be derived from measurement of night time supply losses (these equal night time supply and assume little usage).

A raster grid as shown in Figure 4 can be used to allocate recharge to lumped groundwater balance sub-areas.

4.4 Groundwater flow between sub-areas

Groundwater flow across the boundaries of sub-areas of the water balance area can be calculated by assessing the hydraulic gradient across sections of the sub-area boundary. The method is illustrated in Figure 5. Groundwater levels contours and aquifer transmissivity are required to do the calculations illustrated in the figure. The method works well when groundwater level gradients and aquifer transmissivity do not change much with time. Use of a raster grid to calculate groundwater flow is illustrated in Figure 6.

If changes in groundwater level gradients occur over a historic time period, then these can be explicitly specified to calculate groundwater flow on a time step basis. For prediction runs this can not be done and a more implicit method needs to be used. A simple method would comprise the following:

- Use historical information on groundwater gradients and groundwater volumes in connected sub-areas to relate gradient to difference in volume.
- Predicted groundwater volumes for the two adjacent sub-areas can then be reworked into a hydraulic gradient using the relationship based on historical simulation.
- This method should be considered approximate, particularly if changes in the groundwater volumes are rapid during modelled time steps.

4.5 Interaction between rivers and groundwater

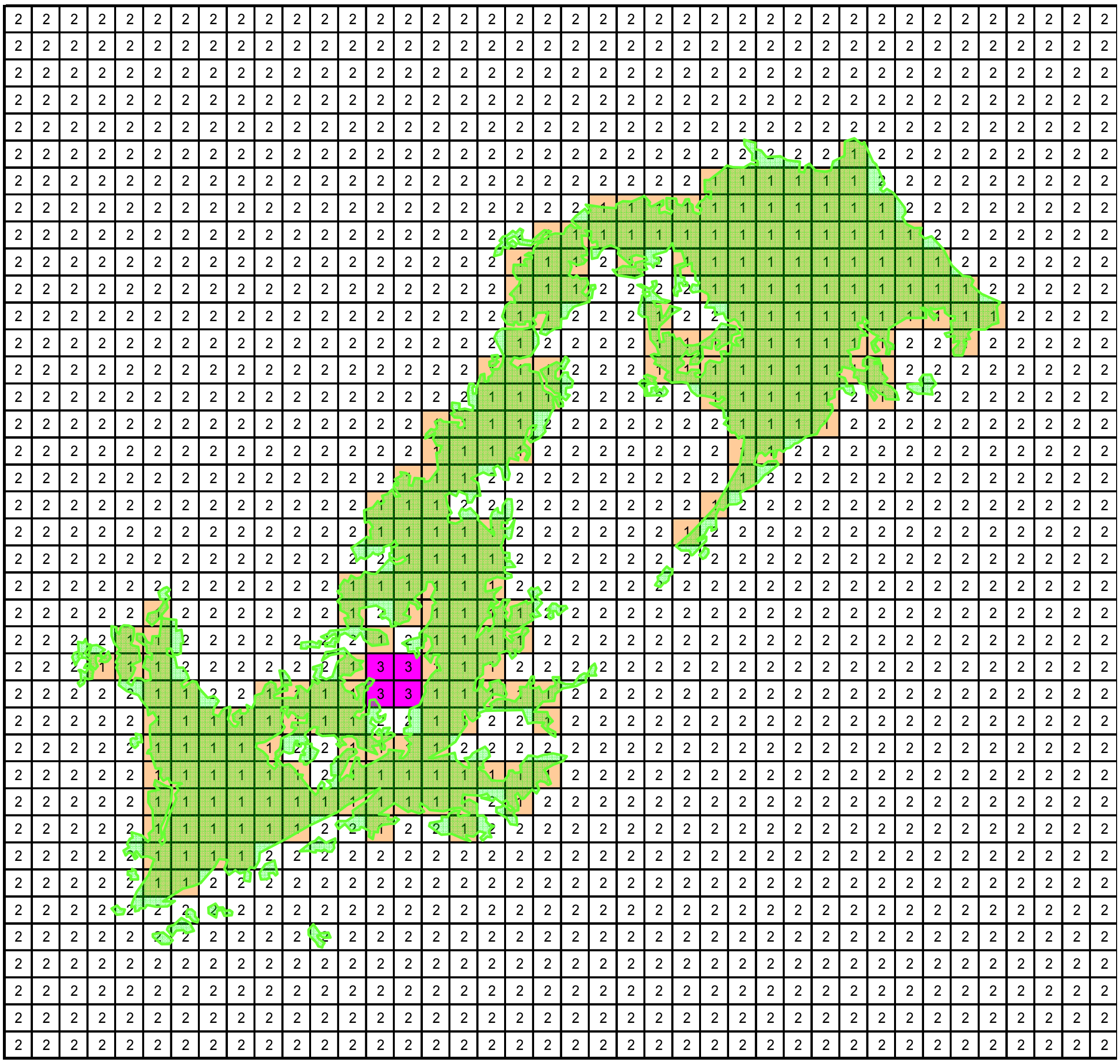
Similar to the calculation of groundwater flows between sub-areas, groundwater flow to and from rivers, which are in continuity with the saturated groundwater, can be calculated. The method is illustrated in Figure 7.

When the river is perched, outflow can be considered to be at a constant rate and as a function of wetted perimeter and a loss coefficient. A river is perched when the groundwater level is fully separated from the river and that thus an unsaturated profile has developed between the river and the underlying groundwater table. This is further illustrated in Appendix A at the end of this Paper.

In distributed groundwater models river/aquifer interaction is based on the relative levels in the river and in the model cell that contains the river, and a conductance term. This allows for dynamic simulation of the interaction. This method is not suitable for lumped water balance models.

For lumped water balance approaches river/aquifer interaction can be simulated through a relationship between groundwater storage and river in or outflow. This approach can only be verified if river flow measurements allow for an estimate of actual gain or loss.

Figure 4: Recharge allocation to raster grid

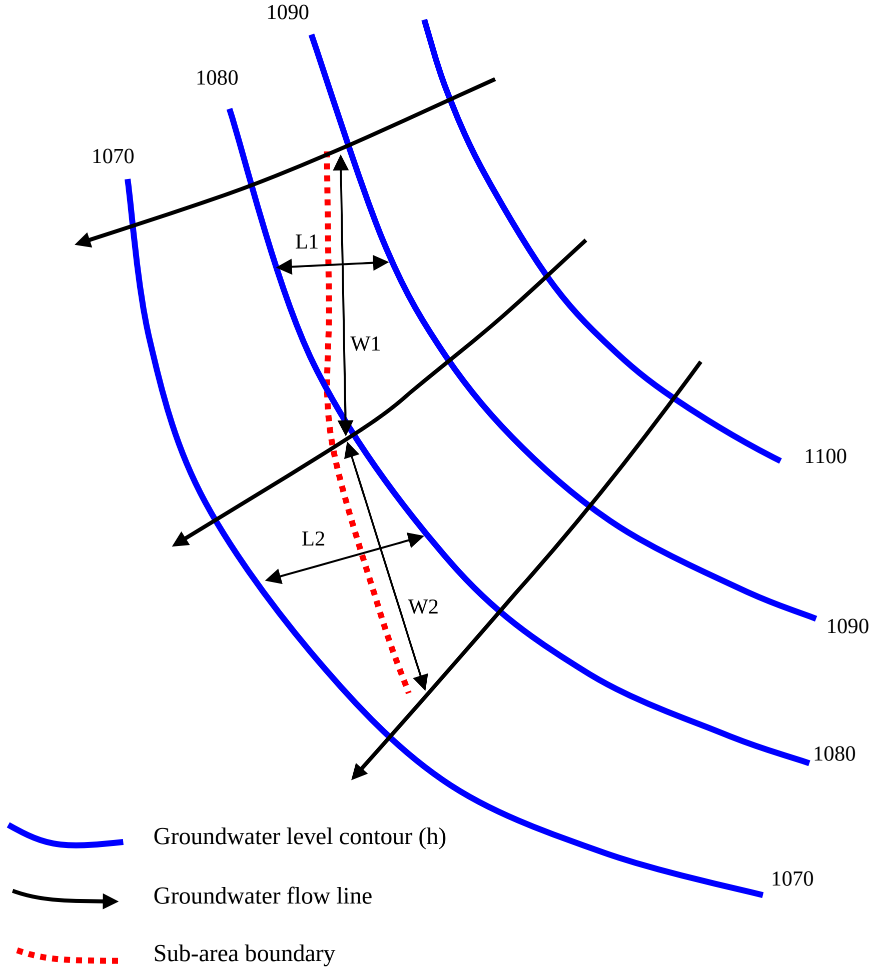


This figure shows irrigated areas as well their representation in the raster grid. The raster grid approximation allows for summation of recharge for defined areas by allocating sub-area codes. In this example a code 1 has been allocated to all of the irrigated area, but sub-areas are easily established by using additional number codes. In this example a code 2 has been used to identify non-irrigated areas where natural recharge from precipitation may occur, while a code 3 is used to identify areas where urban recharge occurs.

The raster method can be set up in a spreadsheet and allows for relatively easy approximation of water balance components for lumped water balance sub-units.

Raster grids are also use in GIS and the method can therefore be used in a GIS environment for groundwater balance assessment.

Figure 5: Calculation of groundwater flow between sub-areas



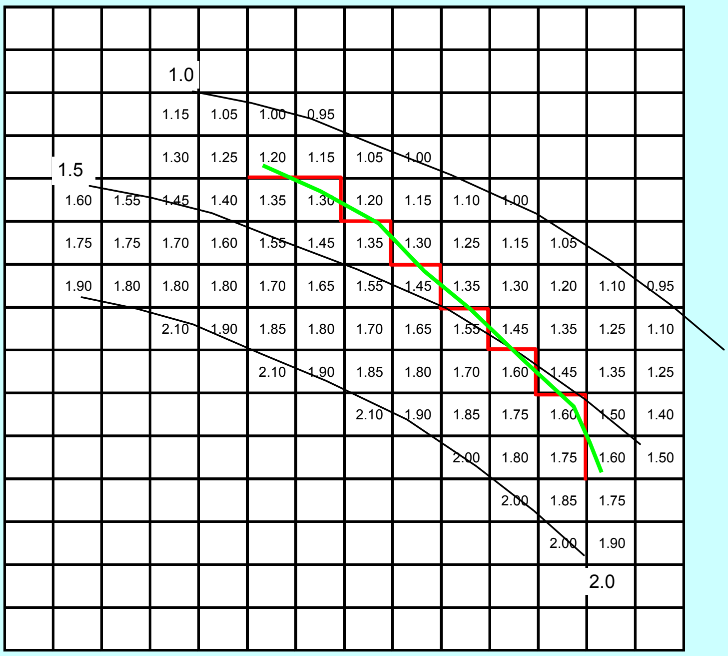
Flow across marked section (in red) calculated as follows:

$$\boldsymbol{GWflow = \sum(W_i * grad_i * kD_i)}$$

Where:

Where:	W_i	-	width of inflow section
	L_i	-	distance between groundwater contours
	$grad_i$	-	hydraulic gradient
			$grad_i = \Delta h_i / L_i$
	KD_i	-	aquifer transmissivity
	h	-	groundwater level (m above datum)

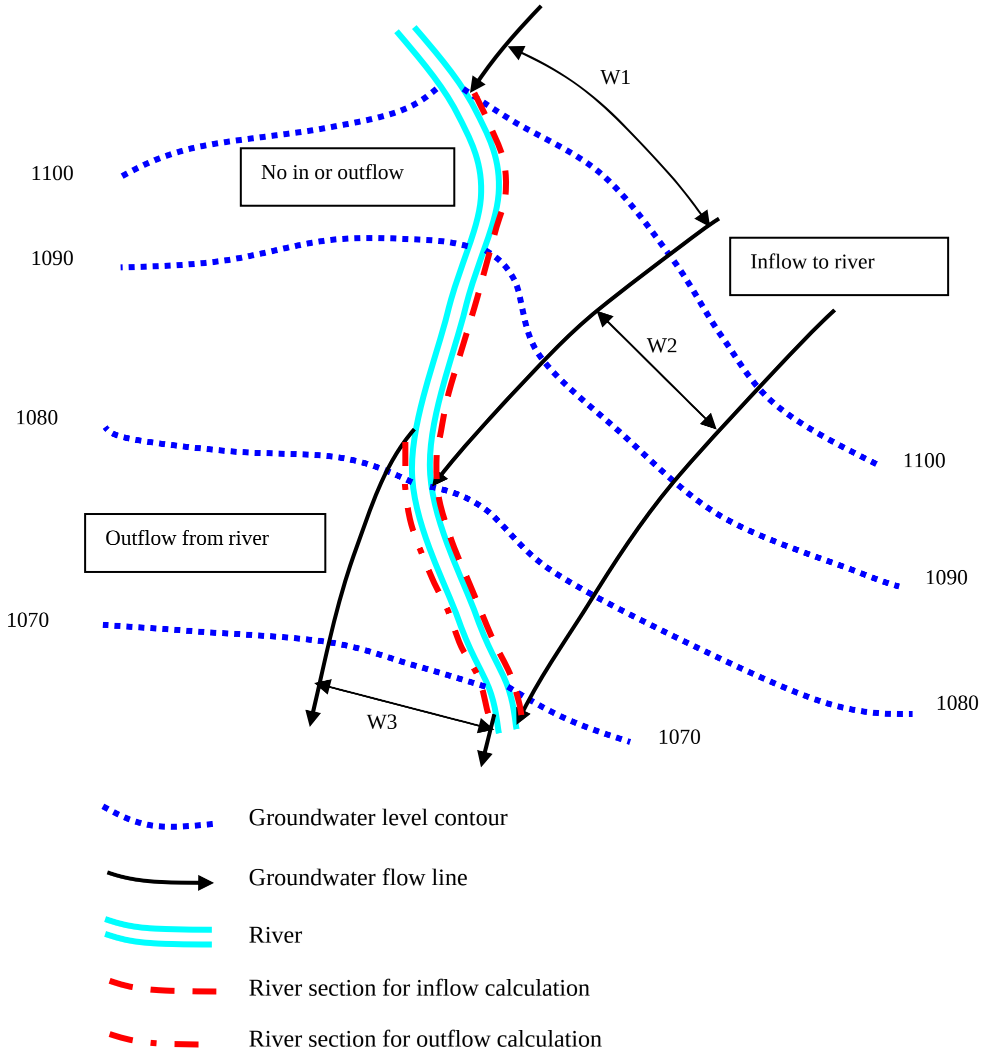
Figure 6: Calculation of lateral groundwater flow using a raster grid



			T =	1000
	h1	h2	delh	Qlat
1	1.35	1.20	0.15	150
2	1.30	1.15	0.15	150
3	1.30	1.20	0.10	100
4	1.35	1.20	0.15	150
5	1.35	1.30	0.05	50
6	1.45	1.30	0.15	150
7	1.45	1.35	0.10	100
8	1.55	1.35	0.20	200
9	1.55	1.45	0.10	100
10	1.60	1.45	0.15	150
11	1.60	1.45	0.15	150
12	1.60	1.45	0.15	150
13	1.60	1.50	0.10	100
14	1.75	1.60	0.15	150
			Sum	1850

This figure shows the use of a raster grid to calculate groundwater flow across sub-unit boundaries. The grid values are derived from interpolation of groundwater levels obtained from observation wells (refer also to Figure 4). In this example the simulated sub-unit boundary (shown in red) comprises 14 sections. And calculation of flow (assuming a transmissivity of 1000 m^2/d) is shown above. This method is reasonably accurate to represent flow across a boundary that is smooth as shown above in green.
Again such calculations can be done in an Excel spreadsheet or in a GIS environment.

Figure 7: Calculation of river/groundwater interaction



Inflow to marked section (in red) calculated as follows:

$$GWIN = \sum(W_i * grad_i * kD_i)$$

Where:
- W_i - width of inflow section
- $grad_i$ - hydraulic gradient
- kD_i - aquifer transmissivity

Outflows from the river calculated in the same way.

4.6 Groundwater abstraction

Information on groundwater abstraction is not always available from direct measurement. If groundwater abstraction can be directly obtained, such as for example as done in Minqin County in Gansu Province with the use of IC cards and flow meters, then a raster gird approach as illustrated in Figure 8 can be used to allocate abstraction to sub-areas. Alternatively, abstraction data available on an administrative unit basis could be used.

Even if groundwater abstraction is directly measured, it may not be recorded for smaller time steps than one year. In this case the abstraction for smaller time steps may need to be calculated as the difference between gross crop water demand (or demand for pre-watering) and surface water allocation.

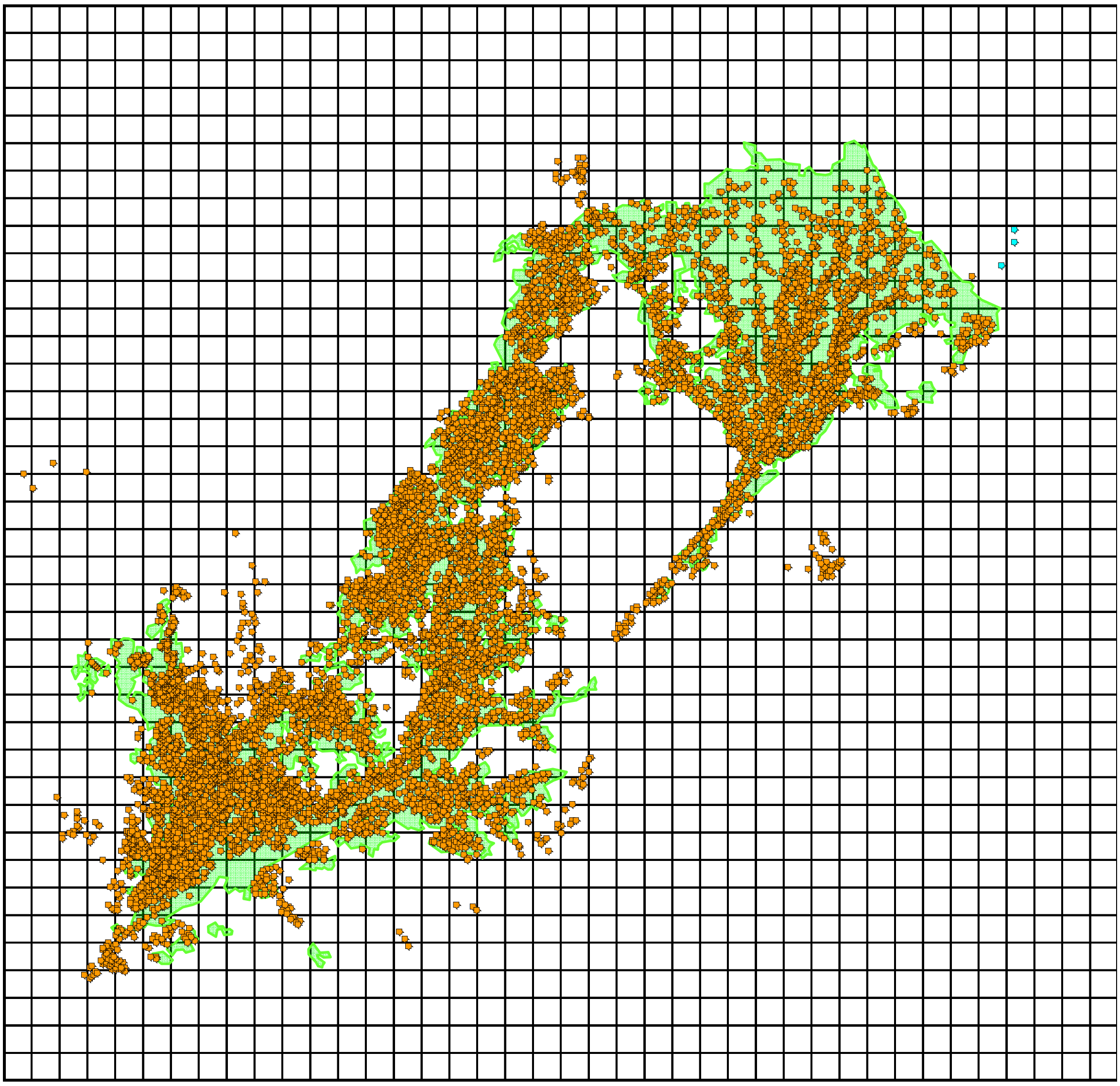
Indirect assessments of groundwater abstraction include using records of electricity consumption and the relationship between well discharge and rate of electricity consumption can be very useful. This method can be reasonably accurate and potentially allows for estimation of abstraction for small time periods, provided electricity consumption records are kept and available to the resource managers.

4.7 Groundwater storage change

In lumped water balance models the groundwater storage change follows from the calculation of all inflow and outflow components for a sub-area. If storage coefficients are known, then the storage change can be used to calculate an average groundwater level change. Actual groundwater level measurements may be used to verify the storage calculations in the model and allow for a degree of adjustment of calculated water balance components.

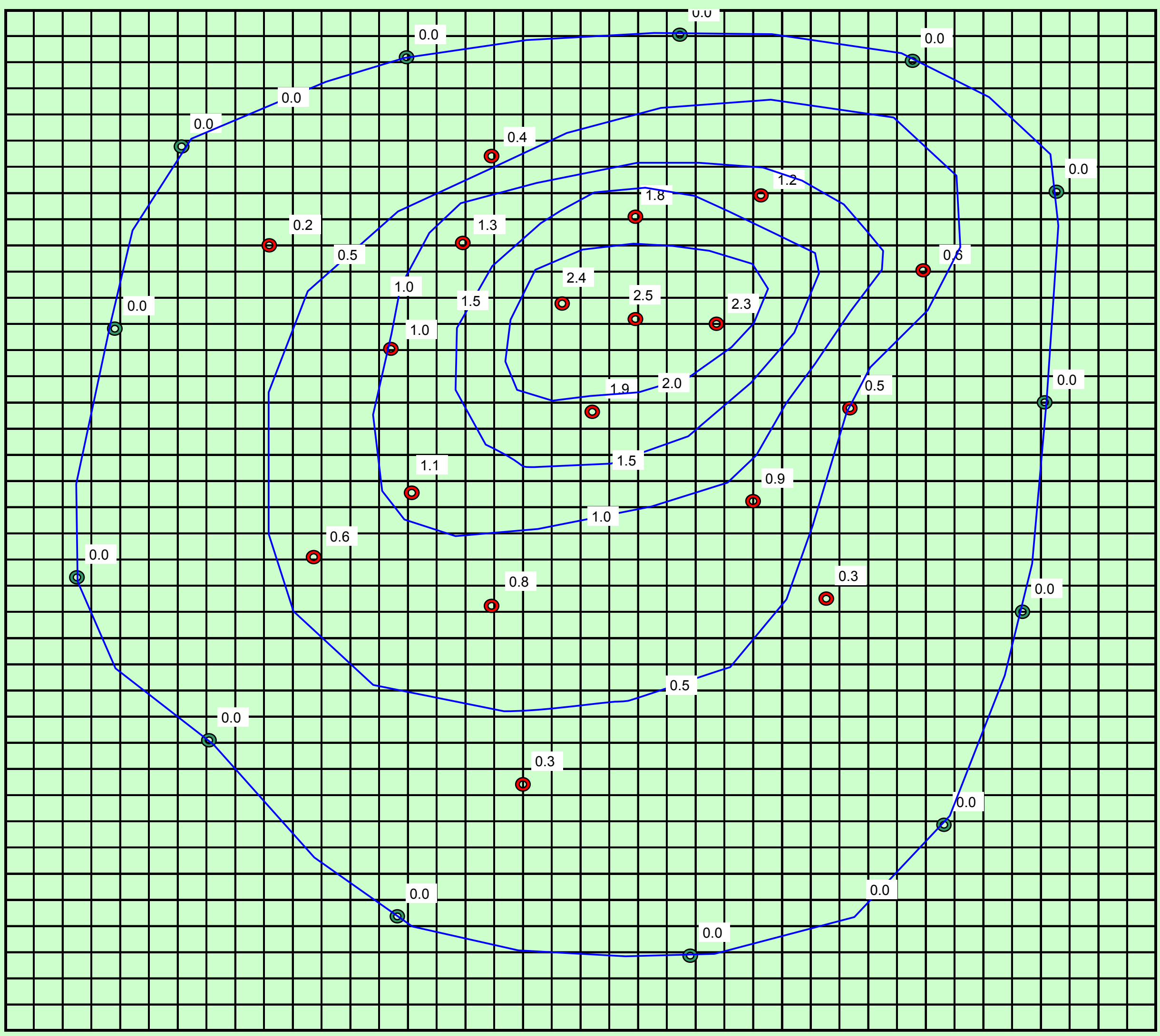
For distributed numerical models, the storage change is implicitly built into the simulation process. Model calibration using observed groundwater levels would allow for adjustment of parameters controlling the magnitude of groundwater balance components. Raster girds can be used, as shown in Figure 9, to calculate storage change within groundwater balance sub-areas.

Figure 8: Abstraction allocation to a raster grid



This figure shows the use of a raster grid to calculate groundwater abstraction for individual grid cells based on the number of active groundwater wells located within grid cells. The figure above shows locations of wells taken from the Minqin database. The locations of wells in the figure are approximate and only serve as illustration.
Numbers of wells can be allocated to raster grid cells using appropriate tools and using raster grid cell and abstraction well coordinates.
Such calculations can be done in an Excel spreadsheet or in a GIS environment.

Figure 9: Calculation of groundwater storage change



0.3 Observed groundwater level change

0.0 Dummy observation point where zero change is assumed

Contour for illustration

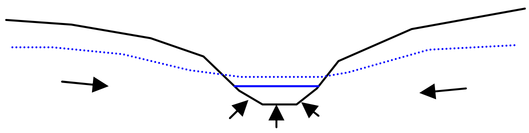
Groundwater level changes are allocated to raster grid cells using an interpolation method such as inverse weighting. Dummy points are introduced to define extent of change (if not done, false edge effects will result).

The values derived for grid cells can be used to calculated storage changes for defined sub-areas, using a storage coefficient value representative for the sub unit. Storage coefficients could be allocated to individual grid cells and storage changes derived for grid cells. Storage change for a sub-unit would then be derived through summation for associated grid cells.

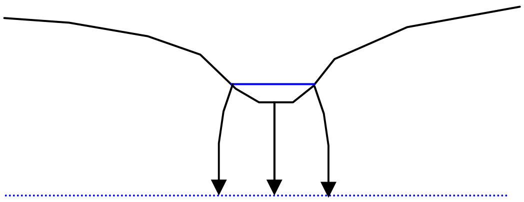
Appendix A

River/aquifer interaction

Gaining river



Perched river



River aquifer interaction (both gaining and losing) is a function of river bed conductance and differences between river level and groundwater level

An unsaturated profile has developed below the river bed and river loss has become independent of groundwater level

Model/ assessment area extent

There is no general rule for the setting of the model extent. It depends on the scope of the assessment and also on available data. A number of basic rules can be employed to help in determining the extent of a model:

- It should preferably extend to natural boundaries such as rivers in contact hydraulic continuity with the aquifer, a groundwater flow divide or an impermeable boundary
- If such natural boundaries do not exist or are too far away, the extent should be sufficiently far away for away from developments that cause changes in the groundwater levels.
- If this is not practical, then a boundary can be specified with user defined boundary conditions (either a specified flow or a specified hydraulic gradient)

Sub-areas

For lumped water balance models, the total model area can be sub-divided into sub-areas. The number of sub-areas will depend on the assessment method, on the characteristics of the model area and on available data. A large number would make the model complex and considerable time may be needed to set up and develop the model. For a method 2 assessment, one would aim at a limited number of sub-areas (probably around 5 or less), while for method three a number up to 10 may be considered.

Sub-areas could represent natural sub-catchments, irrigation command areas, drainage command areas, well fields or administrative units. The choice may be dictated by availability of data. For example when abstraction and irrigation related data are available for administrative units, then there is strong justification for choosing those as sub-areas. Where data is available for irrigation command areas, then those would be better suited as sub-areas.

Figure 2 in the Paper serves as an example; here the sub-areas have been based on surface water irrigation command areas and on a well field area.

Appendix B1

Aquifer types according to geology

Unconsolidated - Generally alluvial sands and gravels that exhibit good transmissivity (depending on grain size and thickness) and are of recent geological origin (Holocene and Pleistocene deposits). Storativity/specific yield are generally high in the range of 5 to 30%, depending on grain size and grain size distribution. Hydraulic conductivity depends also on grain size and grain size distribution and ranges from relatively low values for fine and poorly graded sands to very high for uniform gravels. As an approximate guide, the following values provide an indication:

Type	Hydraulic conductivity range (m/d)*	Storativity
Fine sand	5 - 20	0.05 – 0.20
Medium sand	10 - 40	0.05 – 0.20
Course sand	20 - 80	0.10 – 0.30
Fine gravel	30 -100	0.10 – 0.30
Course gravel	40 - 500	0.10 – 0.30

*low values relate to poorly sorted sands and gravels, while high values relate to a uniform grain size

Consolidated - Consolidated aquifers can include unfractured or partially fractured sandstone aquifers with properties similar to unconsolidated sands and highly fractured dual porosity aquifers. The latter can include limestone formations (sedimentary rocks) and crystalline basement rocks (for example granites and basalts). For those formations the transmissivity and storativity are largely determined by the fracture distribution and the fracture size. Transmissivity can range from very low to extremely high depending on whether fissures are present to transmit groundwater flow. Values in excess of 10,000 m^2/d (derived from pumping test analyses) are not uncommon. Limestone aquifers often show enhanced transmissivity due to dissolution in areas where groundwater flow converges (for example in river valleys). It also depends on the location of fissure horizons with respect to the groundwater level. It is not uncommon to see a significant variation in transmissivity at a single location due to groundwater level variations (high transmissivity when groundwater levels are high). Storativity is largely determined by the fracture porosity and can be much smaller then total porosity. For fractured aquifers, the storativity used in resource assessment ranges from 0.5 to 3% considerably smaller than for unconsolidated and non-fractured sandstone aquifers. Porosity in such aquifers can be as high as 40%.

Karstic - These are extreme cases of consolidated sedimentary aquifer where dissolution has caused large size underground tunnels and cavities. Such groundwater systems can often not be assessed using the porous media assumptions and thus linear groundwater flow assumptions as for the unconsolidated and consolidated aquifers.

Appendix B2

Aquifer types according to extent, layering

Minor	-	Minor aquifers are generally of limited extent and/or yield only small amounts of groundwater because of low transmissivity. Such aquifers maybe locally important for supplying groundwater for potable use
Major	-	Major aquifers are often extensive and of major importance as a resource for irrigation, industrial and potable water supply. Such aquifers exhibit good water transmitting properties although these may vary spatially.
Riverine	-	Such aquifers are in continuity with rivers and significant exchange between the river and the aquifer is possible. Groundwater abstraction would thus be supported by river inflow.
Single layer	-	Such aquifers may have inter-bedded low permeability layers. In resource assessment they are considered as single units within which there may be spatial variability in aquifer properties.
Multi-layer	-	Such aquifers comprise aquifer layers that are over large area separated from each other by low permeability aquitards (such as clay layers). If there is limited variation in groundwater levels with depth due to relatively high permeability in the aquitards, they can be considered as single units in resource assessment. If vertical groundwater levels are significant and data are available to support this, then a multi-layer approach is required.

Document Reference Sheet

Glossary:

Aquifer Saturated underground rock or sediment formation which is sufficiently permeable to transmit water to wells and springs. Groundwater flow is predominantly horizontal.

Aquifer storage The ability of the aquifer to store water in interconnected pores and fractures. Aquifer storage is quantified by a values referred to as storativity and specific yield.

Aquitard A formation that exhibits low hydraulic conductivity and within which groundwater flow is predominantly vertical a small. Examples include clay and silt layers.

Boundary conditions The physical conditions at the boundaries of a system. Examples are model bottom and no-flow boundaries at the lateral aquifer terminus, fixed flux boundaries representing a fixed inflow or outflow of water across that boundary cell, and fixed head boundaries representing piezometric head that is held constant by some external force such as a river or lake. A mathematical representation of boundary conditions must be specified in a numerical ground water flow model.

Calibration The process of adjustment of model input parameters until an agreed match between the modelled and observed groundwater system responses is achieved. The comparison normally relates to groundwater levels and could also relate to river flows, spring flows and groundwater quality.

Conceptual model A simplified yet comprehensive representation or description of how the real hydrogeological system is believed to behave. A quantitative conceptual model includes preliminary calculations, for example, of vertical and horizontal flows and of water balances.

Confined aquifer An aquifer which is overlain by a confining bed (aquitard) of significantly lower hydraulic conductivity which retards the vertical movement of water.

Heterogeneous A porous medium which has different physical characteristics in different locations.

Homogeneous A porous medium which has uniform physical characteristics everywhere.

Hydraulic conductivity The capacity of a porous medium to transmit water through a unit cross-sectional area. Hydraulic conductivity is dependent upon the physical properties of the porous medium and the viscosity of the water and is expressed in units of length/time. The term permeability is commonly used to indicate hydraulic conductivity.

Model A device which represents an approximation of a field situation. Models can be physical, analytical or numerical.

	A physical model is a physical representation of a larger, more complex system. An analytical model is a mathematical representation of a physical system which can be solved using analytical methods. Analytical models are highly dependent upon simplifying assumptions. A numerical model is a discretised representation of a physical system which is solved iteratively using a computer. Numerical models are less dependent upon simplifying assumptions but are highly data and computation-intensive. Numerical models have the advantage of enabling representation of different areas of the physical system using different physical properties.
Perched	Perched groundwater refers to saturated groundwater separated by underlying saturated groundwater by a partially saturated zone. Perched conditions often occur where low permeability formations overly partially saturated aquifers. A river is considered perched, when the underlying groundwater table is separated from the river by an unsaturated zone.
Porosity	A measure of the void or pore space within rocks and sediments (the ratio of the volume of void spaces to the total volume).
Specific yield	The ratio of the volume of water which will drain from a porous medium by gravity to the volume of the porous medium. It is sometimes referred to as effective porosity.
Storativity	The volume of water an aquifer released from an aquifer per unit surface area of the aquifer and per unit change in head.
Transmissivity	The rate of flow of water through a vertical strip of aquifer which is one unit wide and which extends the full saturated depth of the aquifer. Transmissivity is related to hydraulic conductivity by the relationship: $T = Kb$ where T = transmissivity, K = hydraulic conductivity and b = the saturated thickness of the aquifer. Transmissivity is expressed in units of length^2/time. Because the saturated thickness of an unconfined aquifer changes as aquifer storage changes in response to variation to aquifer recharge and discharge, transmissivity of the unconfined aquifer will change.
Unconfined aquifer	An aquifer that is not under pressure.
Water table	The elevation of the water in an unconfined aquifer, referred to also as the phreatic surface when the groundwater table is in continuity with the atmosphere.

Bibliography:

SL document 183-2005 - Technical standard for groundwater monitoring

Related materials from the MWR IWRM Document Series:

Thematic Paper 1.1 Groundwater Flow Modelling

Thematic Paper 2.6/1 Groundwater Management

Thematic Paper 2.6/2 Groundwater Monitoring and its Importance to IWRM

Thematic Paper 2.6/3 Conjunctive Use of Groundwater and Surface Water

Where to find more information on IWRM – recommended websites:

Ministry of Water Resources: www.mwr.gov.cn

Global Water Partnership: www.gwpforum.org

WRDMAP Project Website: www.wrdmap.com

China – UK, WRDMAP

1. WRA

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IWRM Document Series materials, English and Chinese versions, are available on the following project website

WRDMAP Project Website: www.wrdmap.com

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