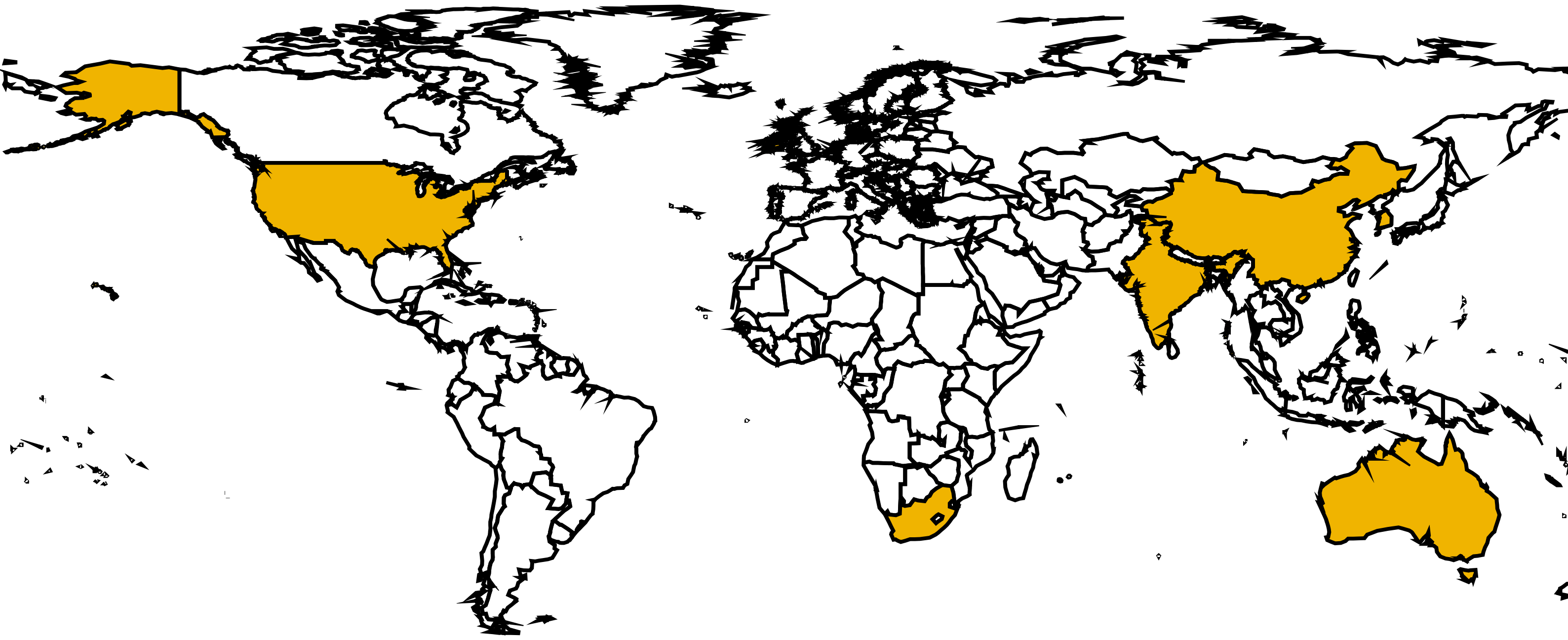
Govt. of India
Ministry of Water Resources
Central Ground Water Board

Assessment of Ground Water Resources

A Review of International Practices



Rana Chatterjee
R K Ray

Faridabad
2014

Govt. of India
Ministry of Water Resources
Central Ground Water Board

Assessment of Ground Water Resources

A Review of International Practices

Rana Chatterjee, Scientist ‘D’
Ranjan Kumar Ray, Scientist ‘C’

Central Ground Water Board (CGWB), Bujal Bhawan, NH-IV, Faridabad, Haryana.
www.cgwb.gov.in, res-cgwb@nic.in, +91 129 2419075, 2412524 (Fax)

Message

Assessment of ground water resources in volumetric terms is imperative in the planning and management of ground water resources. It is also a fact that ground water resource assessment is fraught with uncertainty. Country wide assessment of ground water resources poses additional challenges especially in terms of data availability and maintaining uniformity and comparability of the results.Therefore a trade-off between best scientific techniques and their applicability on a country scale is important. Ground water being a dynamic system, the methodology for assessment requires continuous updating keeping abreast with the evolution in technologies, improvement in data availability and demands of planning requirements.

The first attempt for country wide assessment of ground water resources was made on *adhoc* norms 40 years ago in 1972. During the assessment, it was realized that there is need of proper methodology suiting to the requirements of Indian sub-continent. Subsequently, the Ground Water Overexploitation Committee in 1979 brought out a systematic methodology along with revised norms and procedures for categorization of areas based on the level of ground water development in comparison with ground water recharge. The methodology was further refined by Ground Water Estimation Committee, 1984 (GEC'84); Ground Water Estimation Committee, 1997 (GEC'97) and Committee on methodology for ground water resource estimation in hard rock areas, 2004.

The R&D Advisory Committee on Ground Water Estimation constituted by the Ministry of Water Resources is entrusted with the responsibility to upgrade the methodology and norms. The Committee felt that there should be a review of the international best practices on ground water estimation and the existing methodology practiced in India is to be analysed accordingly.

It is with this background that the present report was compiled. This report is not a mere compilation of international practices, it also proposes a new approach for estimation of ground water resources in India, taking cues from international best practices. It also provides an outline framework for operationalisation of a more robust and scientific ground water resource estimation process in the country.

I laud the efforts of the authors and commend this report as an excellent source material for further deliberations on the subject.

(**Sushil Gupta**)
Chairman, CGWB

Preface

Central Ground Water Board jointly with State Ground Water Departments carries out periodic assessment of ground water resources of the entire country. Such assessments form the basis for planning ground water management interventions like artificial recharge, regulation of ground water use etc. A common methodology is followed in the entire country for assessment of ground water resources.

The methodology followed in India has been systematically evolved and is being periodically refined based on the experience gained from past exercises and advancements in knowledge and tools. The methodology currently being followed for assessment of ground water resources in the country is the one recommended by the Ground Water Estimation Committee'1997 (GEC'97). Ministry of Water Resources has constituted an R&D advisory Committee to review and refine the methodology to ensure more realistic estimation of ground water resources in the country.

Many countries have evolved their own mechanisms and methodologies for assessment of ground water resources based on which the ground water resources in their countries are managed. Ground water resource assessment is also one of the most researched areas in ground water science. Though the different methodologies are based on similar broad scientific principles, they have their unique features. The present document is a review of the international studies related to ground water resource assessment in different countries. The review is based on published literature, personal communications and information available in the public domain.

The authors have done a good job by providing a structured review of the international practices. They also recommend a modified methodology based on international best practices.I am confident that the report will be of interest to the researchers in the field of ground water and will help in evolving a more robust methodology for ground water resource assessment in the Country.

Anita Gupta

(**Anita Gupta**)
Regional Director

Contents

Chapter **Page No.**

Executive Summary

Executive Summary

EXPLOITABLE GROUNDWATER RESOURCES

The quantity of ground water resources, which can be exploited for human needsis defined in the Water policy of a Nation. Many countries have formulated the policies defining the exploitable ground water resource which are mostly based on Safe Yield, Sustainable Yield and Planned Depletion approach.

METHODS FOR ESTIMATION OF GROUND WATER RESOURCES

There are several techniques for estimation of ground water recharge, which can be broadly classified into methods based on physical parameters, chemical and isotopic methods and numerical modelling and empirical methods. All the methods of recharge estimate have inherent uncertainties and therefore it is advisable to use more than one method since these techniques generally complement each other. The choice of technique depends upon the objective of the study and hydrological and hydrometeorological conditions of the area.

GROUND WATER RESOURCES ASSESSMENT AT REGIONAL SCALE

Kansas High Plain and related Aquifers, USA

Regional scale assessment forms the foundation of country scale assessment since it studies the ground water flow system of the entire aquifer system as a unique identity. In some countries, the regional scale implies Regional Aquifer systems like USA whereas in case of countries like Australia and South Africa, regional scale assessment is at basin/ catchment level. In Kansas High plain alluvial aquifers, total availability, ground water accessibility and ground water recharge are estimated. While Availability is estimated based on Storage properties of the aquifer, Accessibility is determined based on Hydraulic Conductivity and Ground Water Level. The Ground Water Recharge is determined based on Water Budget, Soil Moisture Balance and Ground Water Flow modelling technique. Kansas State is divided into five GMD – each GMD has its own ground water management policy. Based on hydrologic conditions and demand considerations, the ground water management policies (Safe/ Sustainable Yield policy, Planned Depletion Policy) are decided.

Murray Darling Basin, Australia

Murray Darling Basin, Australia is covered with Alluvial, sedimentary and fractured hard rock aquifers. Groundwater resources in this basin has been assessed based on Sustainable Yield policy by computing the groundwater balance taking into consideration the climate change and surface-groundwater interaction. Groundwater recharge estimates are carried out based on Water Balance, CMB, numerical modelling techniques. Groundwater draft is estimated using the metered data of groundwater usage by the groundwater abstraction licensee. Sustainable Yield is estimated using Soil-Vegetation-Atmosphere-Transfer (SVAT) modelling approach.

Rietpoort Dolomite Compartment, South Africa

Recharge studies in Rietpoort Dolomite compartment, South Africa provides a comparative analysis of the applicability of various recharge techniques in a hard rock (dolomite) terrain. The dolomite aquifers are characterized by water filled sinkholes and springs. Some of these water bodies have a long record of water level monitoring (e.g. Wondergrat). These long term water level records are useful in application of CRD method. Other important techniques which have proven their applicability in dolomite terrain are Saturated Volume Method, Direct Parameter Estimation method and Chloride

Method. Application of multiple technique provides a better estimation of recharge with high confidence level.

Curragh Aquifer, Ireland

Curragh aquifer in Ireland consists of glacio-fluvial deposits of sand and gravel. Ground water recharge has been estimated using Soil Moisture balance, Well Hydrograph analysis, Numerical Ground Water Modelling and Catchment Water Balance method. With careful choice of data elements and parameters, the recharge estimation of Curragh aquifer through various methods came within the same range i.e. 70% to 85% of effective rainfall.

China-Taiwan

In China, groundwater recharge estimations have been carried out in various climate and hydrogeological situations. In arid climatic zones, both hot and cold deserts, Lysimeter and CMB method have been applied for ground water recharge estimation. In semi-arid plain land areas, Water Balance models, Tritium Injection and Soil Moisture Balance methods were used for assessment of recharge. Taiwan is an island in the neighbourhood of China having hilly and rugged terrain. Baseflow method and Water Budget model have been used in these hydrogeological settings for estimation of recharge.

Urban areas

The mechanism of ground water recharge in urban areas produce interest case studies. Ground Water recharge estimation based on Water Balance, Tracer Studies and numerical modelling, in Seoul, South Korea, Austin, Texas, USA, Perth, Australia and few others have indicated that ground water recharge actually increases with urbanization contrary to the general belief that due to concretization, ground water recharge decreases in city areas. This is primarily because of the recharge from other sources like leakage from water supply and sewage system and return flow from irrigation.

COUNTRY LEVEL ASSESSMENT

South Africa

South Africa is covered with 90% hard rock terrain and 10% alluvial aquifers. The methodology for ground water resources assessment in the country has been developed taking into consideration the prevailing hydrogeological setup and the requirement of the ground water management policy adopted in the country. The basic attribute of the assessment methodology is the determination of Harvest Potential which is then used for estimation of Ground Water Resources Potential. Ground Water Resource Potential is further converted into Groundwater Exploitation Potential, Potable Groundwater Exploitable Potential and Utilizable Groundwater Exploitation Potential. The estimation methodology of South Africa has been recently modified to address the issue of the confidence level of the estimation. The latest methodology is known as Aquifer Assessment Yield Approach. Groundwater uses by various sectors are also estimated. The groundwater resources units are classified in Management Classes in accordance with National Water Act of the country. The classification system takes into consideration among other things, the ground water abstraction with respect to recharge and ground water contamination.

Australia

Ground water resources assessment in Australia is carried out based on Sustainable Yield Policy which differs from State to State within the island continent. National Ground Water Committee (Australia) defines Sustainable Yield as the groundwater extraction "the ground water extraction regime, measured over a specified planning timeframe that allows acceptable levels of stress and protects dependent economic, social and environmental values". In some of the States, Sustainable Yield equals to recharge, in other cases, Planned Storage depletion (groundwater mining) is included in Sustainable Yield estimate. Sustainable Yield is estimated using various hydrogeological methods like hydrograph response, water balance and groundwater modelling. Country level assessment of draft is carried out using crop water requirement and area irrigated and also in some areas through metering. Assessment units are categorized based on level of use, consumptive use as a proportion of inflow and consumptive use as a proportion of water resources. There is a well defined procedure for Reliability Assessment of water resources estimations.

United States of America

The National Scale ground water resources assessment in USA is based on the assessment of the ground water in the aquifers at Regional Scale. Hence, Regional Aquifer System Analysis was carried out for the major aquifer systems of the country. GIS based approaches have been adopted for country level assessment. Maps were prepared depicting – Precipitation, Potential Recharge (rainfall minus evapo-transpiration) and Natural Ground Water Recharge (based on base-flow separation technique). Apart from Natural Recharge estimation, ground water Storage and Discharge have also been carried out. Ground Water Quality assessments have also been carried out on a country scale. Estimations of ground water extraction are also carried out at regular intervals. Latest assessment indicates that irrigation sector is the most important consumer on ground water in United States.

RECOMMENDATIONS

The existing practices of ground water resource estimation in India are comparable to the International Practices. There are many commonalities in the methodology used in India and in countries like South Africa and Australia. Gradual Refinements in methodology were brought in the South African Practice as in India. Guiding principles, outputs and forms of outputs are also comparable. However, in view of the international best practices, a refined methodology has been proposed. The methodology is based on Sustainable Yield Policy. Assessment unit would be aquifer based, alternatively hydrologic unit like micro-watershed (hard rock), doab (alluvium) and catchment area (hilly terrain). Separate assessment to be done for phreatic and confined aquifers. Assessment would be carried out in GIS based approach.Proposed methodology is based on water balance approach. Exploitable groundwater resources would be calculated taking into consideration the minimum flow in the river. The Stage of Exploitation (SOE) would be estimated and validated with the water level data. A Significance Index has been introduced to check the reliability the assessment. The Categorization of assessment unit would be done for the purpose of groundwater resources management. Categorization would involve following criteria – SOE, Extractability Factor (depending on average yield of wells), Temporal Availability Factor (based on dissipation rate during non-monsoon period)and Quality Factor. The total Availability of groundwater resources in the phreatic aquifer would also be assessed incorporating – Replenishable Resource and In-storage Resource. Assessment of groundwater resources in Confined aquifer involves estimation of groundwater storage under pressure condition and ground water draft. GIS based classification is recommended to bring out spatial variation in groundwater condition in confined aquifer.

1

Introduction

Sustainable development and management of ground water resources necessitates assessment of availability of ground water, its existing utilisation and balance resources for future utilisation. In India, ground water resources estimation at a Country/ State level is being carried out at periodical intervals. These estimates form one of the key indicesforidentification of areas for implementation of various government sponsored schemes/ programmes like artificial recharge and rain water harvesting schemes, ground water development schemes, ground water regulation programmes etc. Hence the methodology of ground water resources estimation in the country is reviewed periodically with an objective to bring in refinements in the methodology. For this purpose, the R&D Advisory Committee on Ground Water Estimation, a Standing Committee constituted by Ministry of Water Resources to look into various aspects of ground water resources estimation including review of the methodology decided to explore and examine the best practices adopted by various countries in the field of ground water resources estimation. In view of this, this report was compiled with the objectives to

1. Review international practices in ground water resource assessment
2. To recommend improvements in the existing methodology in view of recent advancements in technologies, past experiences, status of data availability and international best practices.

1.1APPROACH OF THE REPORT

The report is a monograph compiled from the text books, papers published in technical journals, Government Reports published in various countries, information and documents available in the public domain and collected through personal communications.

While organizing the volumes of literatures available on the global practices on ground water resources estimation, it was observed that a major part of the study materials are from certain distinct hydrogeological environments in different parts of the world. Therefore, in this report, case studies from these regions having distinct hydrogeological identity (e.g. alluvial aquifers, USA; hard rock aquifers, South Africa; hard rock aquifers in island continent, Australia etc.) have been discussed in various chapters. The report has been divided into sixchapters. Chapter 1 outlines the approach and the structure of the report. Chapter 2 highlights the policies adopted by various countries to define the exploitable ground water resources. Chapter 3 describes the various techniques of ground water recharge estimation practiced across the globe. Chapter 4brings out certain case studies on the regional scale assessment representing different hydrogeological conditions in various parts of the world. Chapter 5 deals with country level assessment being practiced by some of the countries. Chapter 6 concludes the various approaches adopted by different countries across the globe, evaluates the applicability of these methods in Indian context and suggest refinements in the Indian Groundwater Assessment Methodology based on International Experiences.

2

Exploitable Ground Water Resources

Groundwater is a replenishable but finite resource. It is a part of the water cycle. Groundwater resources in the aquifer gets seasonally recharged and discharged through rainfall and other sources which is reflected in the water level fluctuations. Below this zone of water level fluctuations, the aquifers remain perennially saturated. Excessive withdrawal of groundwater may lead to depletion of ground water storage which may have serious social, economical and environmental consequences. Therefore, historically there has always been an attempt to define the exploitable quantity of groundwater resources i.e. the volume of groundwater which is authorized for withdrawal.

2.1 SAFE YIELD AND SUSTAINABLE YIELD

Two prominent concepts developed to define the exploitable groundwater resources. These are – *'Safe Yield'* and *'Sustainable Yield'*. Historical perspective confirms that both *Safe Yield* and *Sustainable Yield* are evolving concepts. While, *Safe Yield* was defined as early as 1915, the concept of *Sustainable Yield* took its present shape only in 1987. Lee (1915) defined *Safe Yield* as the limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the reserve. Theis (1940) defined *Perennial Safe Yield* as equal to the amount of rejected recharge plus the fraction of natural discharge that it is feasible to utilize. Todd (1959) defines the *Safe Yield* as the amount of groundwater that can be withdrawn from a groundwater basin without producing an undesired result. Any withdrawal in excess of safe yield is an *Overdraft*. Several other attempts have been made to define *Safe Yield*. Few prominent references amongst them are – ASCE (1961, 1972), Freeze and Cherry (1979), Domenico (1972), Bouwer (1978) etc. Taking into cognizance of various literatures on *Safe Yield*, broadly it can be defined as the „attainment and maintenance of a long term balance between the annual amount of ground water withdrawn by pumping and the annual amount of recharge". That is *Safe Yield* is equated with natural recharge.

However, since groundwater is a part of the Water Cycle, therefore, withdrawal of groundwater will not only affect the aquifer but also the groundwater-fed surface water (springs and base flow) and groundwater-dependent ecosystems (wetlands and riparian vegetation). This led to the emergence of the concept of *Sustainable Yield*. Sustainable yield reserves a fraction of *Safe Yield* for the benefit of the surface waters. World Commission on Environment and Development (1987) stated that Sustainable development must meet the needs of the present without compromising the ability of future generations to meet their own needs. According to Bredehoeft et. al. (1982, 1997, 2002), Sustainable groundwater development is determined by Capture of Natural Discharge. Sophocleous (1997, 1998, 2000), Alley & Leake (2004), Kaif et al. (2005) and Seward and Brendock. (2006) defined *Sustainable Yield* from various perspectives.

Sustainability implies the attainment of a new dynamic equilibrium under conditions of widespread development. For equilibrium to occur withdrawals from the aquifer must induce either additional recharge to the aquifer, reduced discharge from the aquifer, or both. This occurs by increasing the hydraulic gradient into the aquifer when the hydraulic head within the aquifer is decreased. These decreases will continue until changes in recharge and discharge balance withdrawals from the aquifer. The most direct evidence of this new balance is long-term stability of hydraulic heads in the aquifer. The Sustainable Yield depends on the rate at which the hydraulic head decrease propagates through the aquifer to the recharge or discharge area. The closer the pumping centres are placed to either the recharge or discharge areas, the more likely it is that additional recharge or reduced discharge can be realized by withdrawals. The rate of propagation is a function of aquifer diffusivity (T/S) and distance to the nearest recharge boundary and the „strength" of the boundary. The higher the diffusivity, the faster the rate of propagation and the more likely it will be that pumping centres located farther away from either the recharge or the discharge areas will influence the amount of recharge and discharge. Strength of recharge boundary implies capacity of the recharge source (eg. River) to feed the aquifer system.

The concepts of *Safe Yield* and *Sustainable Yield* can be generalized using the following diagram. Pristine Ground Water system (fig. 2.1a) is where no groundwater development has taken place. *Safe Yield* in this groundwater system is equal to Natural Recharge (NR). In figure 2.1b, groundwater system has reached a new dynamic equilibrium. The *Sustainable Yield* in this groundwater system is Captured Recharge (CR) + Captured Discharge (CD). However, how much of *Capture* or Groundwater Abstraction amounts to *Sustainable Yield* would depend on the hydrogeological, hydrological, ecological, socioeconomic, technological, cultural, institutional and legal aspects of groundwater utilization, by establishing a reasonable compromise between conflicting interests.

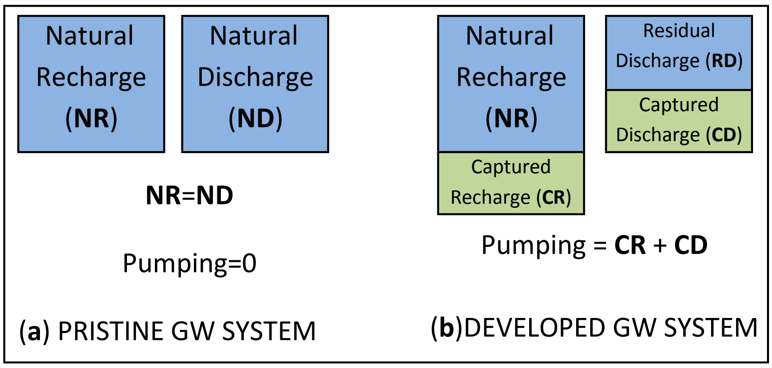


Fig.2.1: Recharge and Discharge in groundwater system
a. Pristine, **b**. Developed

In certain parts of United States of America, Australia etc. a policy of Planned-depletion has been adopted in areas where groundwater depletion in the aquifer cannot be avoided for the sake of the economy of the region. In these areas, a portion of the total storage in the aquifer is allowed to be depleted, the limit of which is decided keeping in consideration the hydrogeological attributes of the aquifer. Till the groundwater storage in the aquifer reaches that limit, the groundwater extraction is permitted. Planned-depletion can be estimated using the specific yield, saturation thickness and areal extent of the aquifer. Similar policy has also been adopted in some other parts of World.

2.2 EXPLOITABLE GROUNDWATER RESOURCES – POLICIES & ESTIMATES BY STATES/ COUNTRIES

Several countries are evolving policies regarding water budget approach. Table 2.1 indicates the approach to groundwater management adopted in several parts of the world. It is based on the table provided in Kaif et. al. (2005) and additional references as indicated.

Table 2.1: Policy and approach on exploitable ground water resources adopted by different countries

Sl. No.	**Country/state**	**Policy & Approach**
1.	Britain	Total abstraction, plus the required stream flow, must be less than recharge. The resource availability status for each river reach and groundwater management unit is assessed. There are four classes of resource availability status indicated by colour code (Environment Agency, Govt. of UK)

Sl. No.	Country/state	Policy & Approach
2.	European Union (Water Framework Directive)	Sustainable yield policy: In a ground water body the “available groundwater resource” means the long-term annual average recharge less the long-term annual rate of flow required to achieve the ecological quality objectives for associated surface waters. Under this directive “good quantitative status” of groundwater is keeping abstraction less than the available groundwater resource (Rejman, 2007)
3.	India	National Water Policy (2002) states that „exploitation of groundwater resources should be so regulated as not to exceed the recharging possibilities, as also to ensure social equity‟. If the annual extraction is more than annual recharge, it is considered „over-exploitation‟. Regulatory measures are adopted in such cases. (MOWR, 2002)
3.	China	New legislation is based on a safe yield policy
4.	Kansas, USA	Groundwater Management Districts (GMD) in east and northwest now have a safe yield policy, but introduced too late to prevent water level declines. Western GMDs have a planned depletion policy.
5.	Arizona, USA	Over-use and falling water levels addressed by legislation that mandates safe yield (balancing abstraction with recharge)
6.	California, USA	Courts have determined “equitable distribution” over large areas
7.	Rhode Island, USA	Safe yield policy
8.	Indonesia	Implied target of reducing abstraction to less than recharge
9.	Arabian Peninsula (Algeria, Oman, UAE, Syria, Jordan, Bahrain, Qatar, Kuwait, Saudi Arabia)	No specific policy. Abstraction is without volume limitation for individuals
10.	Mexico (Guanajuato State)	No specific policy. Efforts in progress to set up groundwater management program
11.	Western Turkey	Safe yield policy since 1960‟s. Now exploring groundwater development using various yield policies

Sl. No.	Country/state	Policy & Approach
12.	Australia	Sustainable yield policy, defined as the ground water extraction regime, measured over a specified planning timeframe that allows acceptable levels of stress and protects dependent economic, social and environmental values. Some States practice the policy of mining of groundwater resource over an agreed timeframe (Storage Depletion). A four-class classification system developed to communicate the status of use and allocation of water resources in relation to sustainable water management (NLWRA, 2007).
13.	Northern Iraq	Safe Yield policy is in general based on annually replenished dynamic reserves. However, in some cases where dynamic reserves are not properly determined, „allowed extraction" is based on static (non-renewable) groundwater reserve from deeper aquifers.

2.3 WORLD GROUNDWATER RESOURCE

In the report entitled „Review of World Water Resources by Country", 2003 by Food and Agriculture Organization of United Nations (FAO), Exploitable Water Resources has been estimated considering factors such as: the economic and environmental feasibility of extracting groundwater; the physical possibility of catching water which naturally flows out to the sea; and the minimum flow requirements for navigation, environmental services, aquatic life, etc. Though this concept varies from country to country but in general the following approaches have been adopted in the above mentioned report for estimating ground water recharge (generated from precipitation within country) which is a part of Internal Renewable Water Resources (IRWR). The groundwater resources in humid areas have been assumed to be equal to the base flow of the rivers where data are available. Where necessary, measured data are corrected to take water abstraction into account. In semi-arid areas, the groundwater resources are obtained from rainfall infiltration estimates or from analyses of measured groundwater levels/heads in aquifers. A summary table of ground water resources of 170 countries and territories are provided in Annexure 1.

2.4 CONCLUSION

The Safe Yield and Sustainable Yield policies are based on environmental considerations. The transition from Safe Yield to Sustainable Yield would be possible only if adequate and firm database are available on aquifer-surface water body interaction. Planned Depletion policy on the other hand is biased towards human demand considerations. Planned Depletion is followed by Zero Depletion Policy. Therefore this policy can be implemented only in areas where strong control over ground water extraction exists.

3

Methods of Ground Water Resource Estimation

The need for reliable estimate of ground water recharge is well recognized. In the last three decades numerous recharge studies have been reported in the scientific literature. A better understanding of the methods, their applicability and limitations is an important pre requisite to choose the appropriate techniques for ground water resource estimation.

3.1 DYNAMICS OF GROUND WATER RESERVOIR AND ASPECTS OF RECHARGE

Changes in ground water storage involves various recharge and discharge processes. Major recharge sources are rainfall, recharge from rivers, recharge from ponds, recharge from irrigation fields etc. Similarly, discharge processes include evapotranspiration, pumping, base flow to rivers etc (Fig.3.1). A brief description of recharge types and recharge mechanisms is given below.

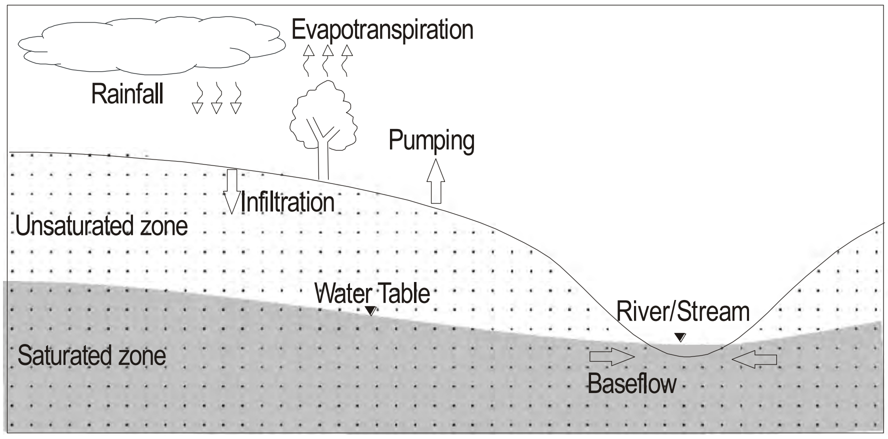


Fig. 3.1: Different processes associated with recharge to ground water.

3.1.1 RECHARGE TYPES

Recharge is defined as the downward flow of water reaching the water table forming an addition to the ground water reservoir (de Vries and Simmers, 2002). Lerner (1997) defines the following types of recharge.

i. ***Direct Recharge***: In this process water is added to the ground water reservoir by direct vertical percolation through the vadose zone. The water that is added to the ground water reservoir in this process is in excess of soil moisture deficit and evapotranspiration.

ii. ***Indirect Recharge***: Water from the surface water courses like rivers and canals percolate to the ground water reservoir through the beds of the surface water courses. This process has been termed indirect recharge.

iii. ***Localised Recharge***: It is an intermediate form of ground water recharge resulting from surface or near surface concentration

Hulme et al. (2001) describe two key types of direct recharge: *potential* and *actual* recharge. *Potential* recharge is the water that leaves the bottom of the soil zone. The term potential recharge was introduced by Rushton (1988). It is the potential amount of water available for recharge from the soil zone. Recharge reaching the water table is *actual* recharge. If the material in the unsaturated zone does not restrict the vertical movement of water, the *actual* recharge (the water reaching the water table) equals *potential* recharge.

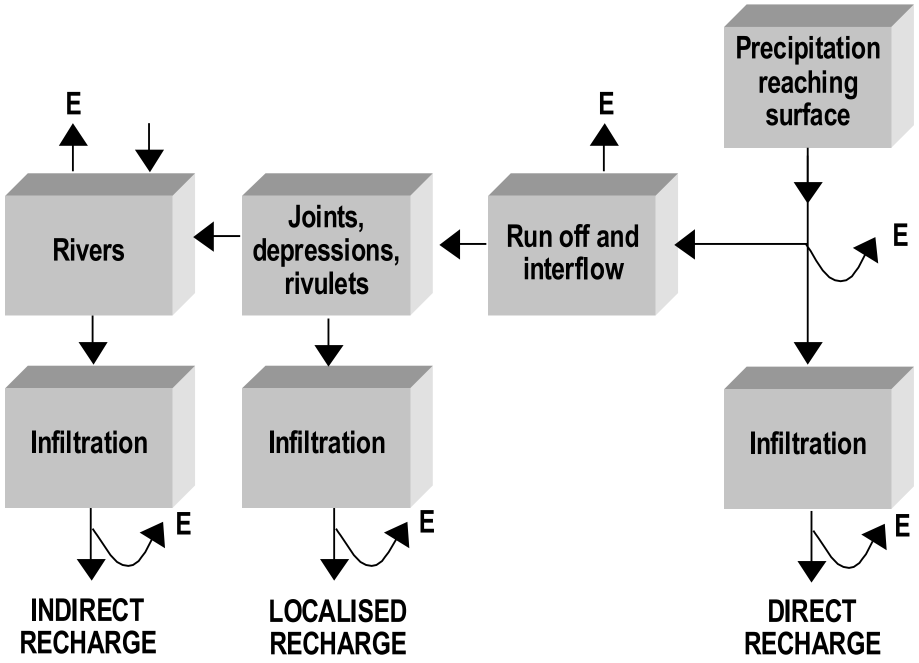


Fig.3.2: Schematic representation of recharge processes (adapted from Lerner, 1997). **E** in the figure stands for Evapotranspiration.

3.1.2 RECHARGE MECHANISM

Ground water recharge involves movement of moisture through the unsaturated zone. There are two major mechanisms, which control such moisture movements:

i. Interstitial (Matrix) Flow
ii. Macropore Recharge

Zimmermann et al., (1967a and b) based on their experiments using environmental and injected tritium as tracers showed that in the case of homogeneous soil without many cracks and fissures, the bulk of water movement from the unsaturated to the saturated zone takes place in layered form and they postulated the piston flow mechanism to explain the interstitial or matrix flow process. In piston flow mechanism recharge water is stacked as layers one above the other. Any fresh layer of water added on the surface pushes an equal amount of water beneath it further down and so on such that the moisture of the last layer is added to the ground water. During this movement the younger water never overtakes the older water. Such type of flow moves largely between individual grains or a fine mesh of fractures (Wood et al., 1997). Macropore recharge, on the other hand occurs through preferred pathways in the soil matrix like cracks, fractures, solution holes, animal burrows, root tubes etc.

de Vries and Simmers (2002) suggest an additional term „preferential flow‟ to describe flow caused by unstable wetting fronts and differential soil physical characteristics within the soil, notably between sandy and clayey sediments. Sukhija et al., (2003), however, use the term „preferential flow‟ to designate macropore recharge.

3.2 GROUND WATER RECHARGE ESTIMATION TECHNIQUES

Various techniques are available for estimation of ground water recharge (Simmers, 1988; Scanlon et al., 2002; CGWB, 2009). For the purpose of discussion in this chapter, the recharge estimation methods have been divided into four broad categories (Table 3.1):

i. Methods based on physical parameters
ii. Chemical and isotopic methods
iii. Numerical Modelling and Empirical Methods.

Table 3.1: Ground water recharge estimation methods

Methods based on Physical Parameters	Chemical and isotopic techniques	Numerical Modelling and empirical methods
1) Water Budget	1) Stable isotopes of Hydrogen and Oxygen	1) Runoff models
2) Base flow measurements	2) Ground water dating	2) Modelling based on unsaturated zone
3) Zero Flux Plane	3) Chloride Mass Balance i. Concentration method ii. Flux method	3) Modelling based on saturated zone
4) Darcian Methods	4) Environmental Tritium i. Peak tritium ii. Total tritium	
5) Lysimeters	5) Injected tritium	
6) Water table fluctuation	6) Other tracers	
7) Cumulative Rainfall Departure (CRD)		
8) Methods based on temperature measurements		
9) Electrical Resistivity measurements		
10) Neutron logging of moisture profiles		
11) Gravity Recovery and Climate Experiment (GRACE)		

3.2.1 METHODS BASED ON PHYSICAL PARAMETERS

3.2.1.1 Water Budget

Water Budget method is based on the principle of Conservation of Mass, wherein it is postulated that total quantity of water in the hydrologic cycle would remain constant. Hence, changes in subsurface water storage can be attributed to recharge and groundwater flow into the basin minus base flow (groundwater discharge to streams or springs), evapotranspiration from groundwater, and groundwater flow out of the basin (Schict and Walton 1961). The water budget can be written as:

$$R = \Delta S^{gw} + Q^{bf} + ET^{gw} + Q^{gw}_{off} - Q^{gw}_{on}$$ ....3.1 (Healy and Cook, 2002)

Where R is recharge, ΔS^{gw} is change in subsurface storage, Q^{bf} is base flow, ET^{gw} is evapotranspiration from groundwater, Q^{gw}_{on} and Q^{gw}_{off} are the water flow onto and off the site such that $Q^{gw}_{off} - Q^{gw}_{on}$ represents net subsurface flow from the study area and includes pumping; all terms are expressed as rates (e.g., mm/year).

The most common way of estimating recharge by the water-budget method is the indirect or “residual” approach, whereby all of the variables in the water-budget equation except *R* are measured or estimated, and *R* is set equal to the residual.

3.2.1.2 Base flow measurements

Use of base flow discharge to estimate recharge is based on a water-budget approach, in which recharge is equated to discharge. Base flow hydrographs (plots of stream flow vs. time) are studied to identify and separate different stream flow end members such as rainfall, soil water, groundwater, and bank storage. Various approaches are used for hydrograph separation, including digital filtering (Nathan and McMahon 1990; Arnold et al. 1995) and recession- curve displacement methods (Rorabough 1964). Chemical and isotopic techniques are also applied to infer the sources of stream flow from different end members (Hooper et al. 1990; Christophersen and Hooper 1992). This approach is data intensive. It is useful mostly for watersheds with gaining streams.

3.2.1.3 Zero Flux Plane

Zero Flux Plane (ZFP) in the unsaturated zone represents a plane where the vertical hydraulic gradient is zero. The ZFP separates upward from downward water movement. The rate of change in the storage term between successive measurements is assumed to be equal to the drainage rate to the water table or the recharge rate. The method was first described by Richards et al. (1956) and has been used in several studies consequently (Royer and Vahaud 1974; Wellings 1984; Dreiss and Anderson 1985; Healy et al 1989). The method involves soil matrix potential measurements to locate the position of the ZFP and the soil water content measurements to estimate storage changes

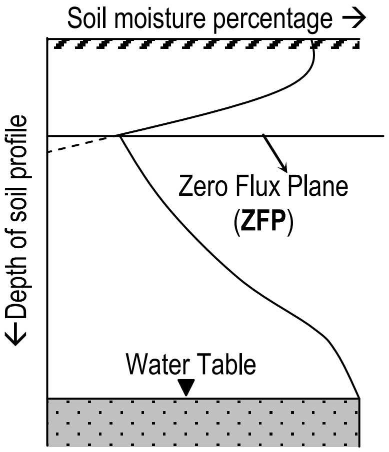


Fig 3.3. Schematic representation of the Zero Flux Plane (**ZFP**)

3.2.1.4 Darcian Methods

Darcy"s law quantitatively describes flow of water through a porous medium. This law can be applied for estimation of ground water recharge both in the unsaturated zone (Soil zone above the water table) and saturated zone (Soil zone below the water table). Recharge (R) is estimated as

$$R = -K(\theta) dh/dl \text{ .... } (3.2)$$

Where R is the recharge, $K(\theta)$ is the hydraulic conductivity at the ambient water content θ and dh/dl is the hydraulic gradient. For thick unsaturated zones where the water movement is essentially gravity driven, gradient is considered as one (unit gradient assumption) (Gardner 1964; Childs 1969;Chong et al. 1981; Sisson 1987). Thus the recharge rate equals the hydraulic conductivity at the ambient water content.

Darcy"s law is used to estimate flow through a cross section of an unconfined or confined aquifer. This method assumes steady flow and no water extraction. The subsurface water flux (q) is calculated by multiplying the hydraulic conductivity by the hydraulic gradient. The hydraulic gradient should be estimated along a flow path at right angles to potentiometric contours. The volumetric flux through a vertical cross section of an aquifer (A) is equated to the recharge rate (R) times the surface area that contributes to flow (S):

$$qA = RS \text{ ....} 3.3$$

The cross section should be aligned with an equipotential line. Theis (1937) and Belan and Matlock (1973) used this method to estimate recharge rates. Saha and Agrawal (2006) used the above method to estimate base flow to a river in a water balance study.

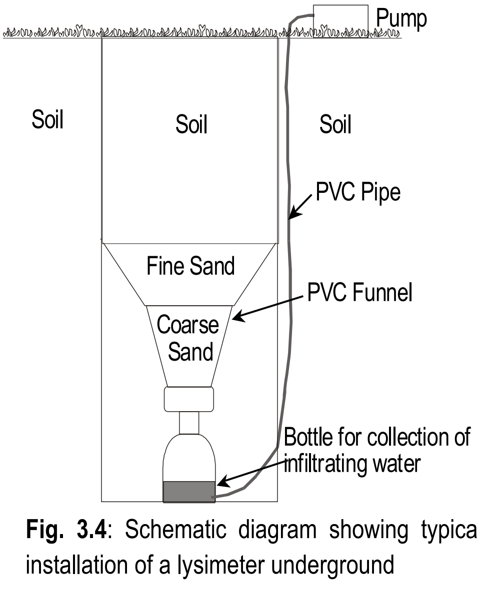


Fig. 3.4: Schematic diagram showing typical installation of a lysimeter underground

3.2.1.5 Lysimeter

Lysimeters consist of containers filled with disturbed or undisturbed soil, with or without vegetation that are hydrologically isolated from the surrounding soil. Lysimeters are used for the purpose of measuring the components of water balance. Since installation of lysimeters is costly, lysimeters with small surface areas are used and are installed at shallow depths. Ideally, for recharge estimation, a lysimeter should be large and deep and extend into the water table (Jones & Cooper, 1998). However, it is seldom practicable. Lysimeters are not routinely used for recharge estimations. They are more useful for estimation of evapotranspiration.

3.2.1.6 Soil moisture budgets

Groundwater recharge can be estimated by the soil moisture balance approach. Soil moisture budgeting, taking into account evapotranspirational abstraction from precipitation, provides a measure of moisture available for runoff and infiltration. This can be done by Thornthwaite's Book keeping method of moisture balance.

3.2.1.7 Water Table Fluctuation (WTF)

Water Table Fluctuation (WTF) method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. It is the most widely used method for estimating recharge. Recharge is calculated as:

$R = S_y\, dh/dt$ ………………. (3.4)

Where S_y the specific yield, h is is water-table height, and *t* is time (Healy and Cook, 2002). Water Table Fluctuations represent spatially averaged recharge. Determining representative values of Sy is a major difficulty in applying this method. Another difficulty lies in ensuring that the fluctuations in water levels are due to recharge and are not the result of changes in atmospheric pressure, the presence of entrapped air or other phenomena such as pumping.

3.2.1.8 Cumulative rainfall departure (CRD)

Cumulative Rainfall Departure (CRD) is the departure of rainfall in the period of assessment from the mean rainfall of the preceding time. Bredenkamp et al., 1995 showed that natural groundwater level fluctuation is related to that of CRD. They showed that such relationships could be used to quantify ground water recharge. In this method, r/S_y (r = percentage of CRD, which results in recharge and S_y= Specific yield) ratio is estimated through an optimisation process, which minimises the difference between calculated and observed water level fluctuations over a specific time interval. Thus with known S_y, r is estimated. Recently, the method was revised to account for trends in rainfall time series (Xu and Van Tonder, 2001). Groundwater levels of fractured aquifers with small storativity are particularly sensitive to rainfall recharge. Simulation of water levels based on the CRD method and hence recharge estimation is fairly accurate in these cases, provided that S_y can be determined.

3.2.1.9 Methods based on temperature measurement

Anderson (2005) provides an exhaustive and critical review of application of heat measurements in hydrogeological studies. The subsurface zone can be broadly divided into surficial zone followed by the geothermal zone. In geothermal zone, which extends beyond around 10m, temperatures gradually increase with depth. The temperature profile in this zone is expected to be linear with an increase in temperature of 1° C per 20 to 30m of depth. Recharge and discharge processes perturb the linear temperature profile. In general, recharge results in a concave upward temperature profile while discharge results in a convex upward temperature profile (Fig 3.5).

Within the surficial zone (Fig 3.5), temperature is influenced by seasonal heating and cooling of the land surface. Temperature profiles in surficial zone potentially provide information about seasonal recharge/discharge events from precipitation and interchange with surface water.

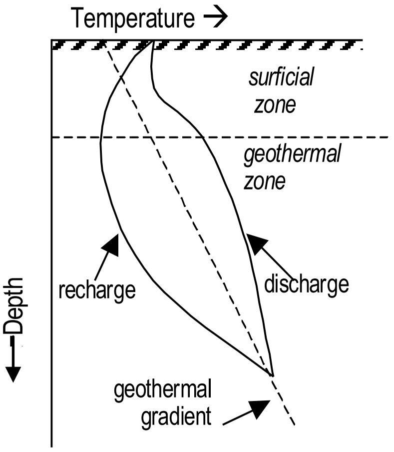


Fig.3.5: Schematic temperature profiles showing deviation from geothermal gradient caused by recharge and discharge processes (After Taniguchi et al.,1999 and Anderson, 2005)

Transient heat flow equations are used to define the vertical variations in temperatures. These equations are then solved to get the recharge and discharge rates (Suzuki, 1960; Bredehoeft and Papadopulos (1965) and Stallman (1965); Ferguson et al. (2003) and Taniguchi, 2003).

3.2.1.10 Electrical Resistivity

Israil et al. (2006) attempted to establish a linear relationship between the resistivity of the unsaturated top layer and the recharge estimated using tritium injection technique for the piedmont zone in the Himalayan foothill region, India. They proposed that ground water recharge could be approximated through resistivity measurements.

Khan and Sharma (2003) prepared isopachs derived from electrical resistivity surveys and from these isopachs estimated ground water potential in the arid regions in parts of Jodhpur district. However, the resources thus estimated do not represent the annual recharge rate (Ray and Thambi, 2003) rather it represents the static resources.

3.2.1.11 Neutron logging of moisture profiles

Recharge can also be estimated by taking soil moisture profiles and calculating the difference in volumetric moisture content before and after the recharge event. Calibrated neutron probe is used to construct the soil moisture profile from the ground surface to the water table. The method provides a conservative estimate of recharge as macropore flow by passes the soil matrix and is not represented in the soil moisture estimates (Flint et al., 2002). Chand et al., 2005 applied neutron moisture probe technique to estimate recharge to ground water in Hyatnagar watershed, Andhra Pradesh.

3.2.1.12 The Gravity Recovery and Climate Experiment (GRACE)

The Gravity Recovery and Climate Experiment (GRACE; Tapley et al. 2004) is a satellite mission jointly managed by the US National Aeronautics and Space Administration (NASA) and the German Aerospace Centre (DLR). It is based on observations of satellite orbit perturbations, which are caused by gravitational anomalies near the land surface. These variations represent all sources of mass variability like ground water, surface water storage, snow, biomass etc., ground water storage changes being the most significant one. Seasonal and inter annual changes in Terrestrial Water Storage (TWS) are quantified using data obtained from the GRACE. Due to the nature of the GRACE technique, the accuracy and reliability of the derived information on water-storage change increase with the size of the region, the averaging time period, and the amplitude of the changes themselves. Rodell and Famiglietti (1999, 2001) estimated that the minimum region size in which GRACE could resolve water mass variability would be about 200,000 km^2. Error sources not foreseen before launch have impacted the effective resolution, so that based on the analysis of Swenson and Wahr (2006), the figure may be closer to 500,000 km^2, if an optimized data filtering and smoothing technique is used. According to Jackson (2002) only changes in water storage and not an absolute mass of water storage can be derived from gravity measurements.

3.2.2 CHEMICAL AND ISOTOPIC METHODS

3.2.2.1 Stable isotopes of hydrogen and Oxygen

The stable isotope (Deuterium and Oxygen-18) composition of precipitation undergoes variations due to altitude, latitude, amount of rainfall, temperature, etc. The heavy isotope composition of groundwater can be helpful as an indication of the genesis and mixing of groundwater in hydrogeological studies (Gat and Gonfiantini 1981). Stable isotopes of Hydrogen and Oxygen provide information on recharge sources and processes involved in ground water recharge. However, it is generally difficult to quantify the recharge rates. Analysis of stable isotopes of water provides an independent approach for evaluating the relative effects of regional macropore recharge.

3.2.2.2 Ground water dating

Ground water dating refers to estimating age of ground water. Age of ground water, in turn, refers to the period of time that has elapsed since the water moved deep enough into the ground water zone to be isolated from the earth‟s atmosphere (Freeze and Cherry, 1979).

Many radioactive isotopes are used for dating ground water. Most common methods include ^{14}C, $^{36}Cl/^{35}Cl$ ratio, ^{3}H, $^{3}H/^{3}He$ ratio, CFC etc.

In an unconfined aquifer, ground water ages increase with depth. Ground water recharge can be estimated by dating ground water at several points in the vertical profile (Cook and Solomon, 1997). The recharge rates thus obtained are the average recharge rates for the period represented by the age of the ground water. Ground water flow velocities in confined aquifers can also be estimated by ground water dating (Scanlon et al., 2002).

3.2.2.3 Chloride Mass Balance

Eriksson and Khunakasem (1969) first proposed that chloride concentration in ground water could be used to estimate recharge flux. Allison and Hughes (1978) modified the method and since then it has been applied by several authors (summarized in Allison, 1988). The chloride mass-balance (CMB) approach is based on the premise that the flux of chloride (Cl) deposited at the surface equals the flux of Cl carried beneath the root zone by infiltrating water. Two approaches have been described in Sukhija et al., 1988. Concentration method and flux method.

<u>Concentration method</u>: In concentration method recharge can be estimated on the basis of chloride balance

$$C_s R_c = C_p P \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

$$R_c = C_p P / C_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

Where R_c is the long-term recharge, C_s is the average conc. of chloride in the soil profile, P is the precipitation and C_p is the chloride concentration in rainfall including dry fall out. The method can be applied both in the unsaturated zone (Allison and Hughes 1978; Scanlon 1991, 2000; Philips 1994) and saturated zone (Eriksson and Khunakasem 1969; Wood and Sanford 1995 Cook et al, 2001 etc.). For the saturated zone calculations, chloride concentration of ground water is compared with chloride concentration in precipitation.

<u>Flux Method</u>: In this method, first the flux of input environmental chloride is established from the chloride content and the corresponding rainfall data. Then the turnover time (Turnover time t is the time required for the soil water to leave the unsaturated zone and enter the ground water system) is obtained from the ratio of the total chloride abundance in the profile upto the water table and its input flux (Eq.2.7). Finally recharge R_f is estimated by dividing the total moisture content by the turnover time (Eq.2.8).

$$\mathit{Turnovertime} = \frac{\mathit{TotalChlorideabundanceinthesoilprofile}}{\mathit{Averageinputfluxof\ Chloride}} \ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

$$\mathit{Recharge\ Rate} = \frac{\mathit{Totalmoisturecontentinthesoilprofile}}{\mathit{Turnovertime}} \ldots\ldots\ldots\ldots\ldots\ldots (3.8)$$

3.2.2.4 Environmental tritium method

Tritium as tritiated water is considered an ideal tracer for water movement studies with its sufficiently long half life of 12.3 years and low radiological toxicity. Small quantities of the tracer can be used in soil experiments due to its high detection limits by using liquid scintillation analysis

(Dharmasiri). There are two variants of environmental tritium methods: total and peak tritium. The methods are applied and discussed in Sukhija and Shah, (1976).

Peak tritium method: Owing to many open-air thermonuclear tests, concentrations of tritium in global precipitations of 1963 were found to be higher than the natural cosmic ray level by a factor of 10 to 1000. Studies involving environmental tritium attempt to trace this tritium spike in the soil profile. Total moisture content within the surface layer and the depth at which the tritium spike was encountered gives the total recharge during the period starting from the year 1963 to the year of study. As on date it has limited applicability as even in deeper water table areas, the tritium peak is expected to have reached the water table or must be attenuated considerably to be detectable (Rangarajan and Athavale, 2000)

Total tritium method: In total tritium method recharge is estimated by comparing the total tritium present in the profile (unsaturated and saturated) with the total tritium precipitated at a given site.

3.2.2.5 Injected tritium method

In the injected tritium method, the moisture at a depth below the shallow root zone in the soil profile is tagged with tritiated water. The tritium labeled layer of moisture is displaced downwards as a result of downward movement of recharge water. The displaced position of the tracer is indicated by the peak in the concentration distribution of tritium. The moisture content of the soil column between tagged depth and the displaced depth of the peak in the soil core corresponds to the natural recharge to ground water over the time interval between injection of tritium and collection of soil core. Injected tritium method (Zimmermann et al., 1967b; Munnich, 1968) assumes piston flow model for movement of water and provides at point measurements of natural recharge.

3.2.2.6 Other tracers

A tracer is a matter (e.g. salt) or energy (e.g. temperature) carried by water, which will give information concerning direction and/or velocity of water in the aquifer. Davis et al., (1980) reviewed the available tracer techniques and they grouped the tracers to nine types: water temperature, solid particles, ionized substances, stable isotopes, radioactive tracers, organic dyes, gases, and fluorocarbons. Anionic tracers (Cl, Br, I) and dyes are in use for many years. These tracers can be used for estimation of recharge. Br is used for estimation of return flow from irrigation. Cobalt-60 as an applied tracer has been used for estimation of ground water recharge in parts of India (Nair et al., 1978; Rao, 1983; Chandrasekharan et al. 1988).

3.2.3 NUMERICAL MODELLING AND EMPIRICAL METHODS

Mathematical modelling or numerical modelling involves representing the natural system in terms of simplified mathematical equations. Mathematical modelling can be applied to surface water studies, unsaturated soil zone studies or the saturated zone studies. Surface water studies are represented by Rainfall/runoff models or watershed models and usually provide recharge estimates as a residual term in water-budget equation. Some models are termed lumped and provide a single recharge estimate. Some provide spatially distributed recharge estimates.

As summarized by Scanlon, 2002 unsaturated-zone modelling is used to estimate deep drainage below the root zone or recharge in response to meteorological forcing. A variety of approaches are used to simulate unsaturated flow like soil-water storage-routing approaches (Flint, 2002, Walker, 2002), quasi-analytical approaches and numerical solution to Richards equation (Stothoff, 1995; Simunek et al., 1996; Hsieh et al., 2000).

For the saturated zone, inverse ground water modelling approaches can be used to estimate recharge rates. Recharge rates here are constrained from water levels, hydraulic conductivity and other parameters (Sanford, 2002). However, inversion using hydraulic head data only is limited to estimating the ratio of recharge to hydraulic conductivity. Recent studies have used joint inversions that combine hydraulic heads and ground water ages to further constrain inverse modelling of recharge. Mixing cell models (Scanlon et al., 2002) have been used to delineate sources of recharge and estimate recharge rate on basis of chemical ad isotopic data.

Empirical relationships have been developed for computation of natural recharge to ground water from rainfall based on the studies undertaken on correlation of ground water level fluctuation and rainfall. In several instances, based on point recharge estimates, rainfall recharge relations in terms of percentage are worked out, which is further utilized to estimate recharge from rainfall (Rangarajan and Athavale, 2000).

3.2.4 ESTIMATING EVAPOTRANSPIRATION AND GROUND WATER DRAFT

In traditional water balance calculations, estimations of evapotranspiration and ground water drafts pose the biggest challenges. Evapotranspiration is the combined process of evaporation from surface water and transpiration through vegetations. Potential evapotranspiration is the maximum obtainable value of evapotranspiration in wet soil condition (Scozzafava and Tallini, 2001). Potential Evapotranspiration is the upper limit of evapotranspiration. Actual evapotranspiration limited mostly by availability of water in the soil zone is always less than potential evapotranspiration. Pan evaporimeters provide measurement of potential evapotranspiration (PET). Thornthwaite (Thornthwaite and Mather, 1957) method is used to estimate potential evapotranspiration (PET) based on average atmospheric temperature and an empirically derived „thermic index". Scozzafava and Tallini, 2001 describe a method for estimating actual evapotranspiration using Thornthwaite equation. Weighing lysimeters are generally used for accurate measurement of actual evapotranspiration. Surface Energy Balance (SEBAL) is a remote sensing based technique which is used to estimate evapotranspiration.

Direct measurement of ground water draft at sample locations can be done by installing water meters. However, often indirect methods are used for estimation of ground water draft owing to the difficulties in metering ground water draft at all pumping sites. Frenzel (1985) compared three methods to estimate irrigation pumpages using field data from a study area, where pumpages were accurately metered. The estimates were based on power consumed, crop consumptive use (using empirical formula) and instantaneous discharge method (several measurements of instantaneous discharge are extrapolated to estimate the seasonal pumpages). A statistical analysis showed that instantaneous discharge method was in close agreement with metered values. Rao et al., 2004 present a heuristic optimization algorithm for estimation of regional draft and recharge based on point observations. Saha and Agrawal (2006) estimated ground water draft based on plot by plot survey of abstraction structures, capacity of pumps fitted in them and the duration of pumping. Ground water withdrawal for domestic purposes can be estimated on the basis of population and per capita consumptions (CGWB, 1997; Saha and Agrawal, 2006).

Ground water draft estimation is fraught with uncertainties mostly because of uncertainties in the basic data. As described by Birkle et al., (1998) the actual number of abstraction structures and the actual ground water draft in Mexico metropolitan zone could be much higher than the official estimates because of large number of illegal constructions. Similarly in Spain, the number of wells is officially estimated at approximately half a million, but in fact more than one million groundwater uptake points may exist (Custodio et al., 1998)

3.2.5 APPLICATION OF REMOTE SENSING IN GROUND WATER RECHARGE ESTIMATION

Remote sensing has the general advantage of providing a spatially distributed measurement on a temporal basis. However, remote sensing only observes the surface of the earth. Remote sensing has been widely used as a tool in assessment of ground water potential (Farnsworth et al., 1984; Waters et al., 1990; Engman and Gurney, 1991 and Meijerink, 2000). Meijerink (2000) recognizes that the value of remote sensing in recharge studies and suggests that this technique can provide both qualitative and quantitative information.

Photography and visible and near infrared satellite observations are widely used in ground water exploration. An alternative approach is microwave remote sensing. As described by Jackson (2002), microwave remote sensing provides a direct measurement of the surface soil moisture. Advantages of microwave remote sensing are that it can be used even through cloud cover. Further the measurements can be done even at night.

The Gravity Recovery And Climate Experiment (GRACE) mission as described elsewhere is also a remote sensing tool that studies the variations in gravitational field of the earth and translates it into variation in Terrestrial Water Storage (TWS).

3.3 CONCLUSIONS

The methods and techniques described above have their own advantages and limitations. None of the methods described above has a clear-cut advantage over other techniques. They differ in their applicability mostly in terms of estimated recharge rates, areas and time periods the estimates represent.

Major sources of uncertainties and inaccuracies in recharge estimations (Healy and Cook, 2002) are.

i) Spatial and temporal variability in process and parameter values
ii) Measurement errors and
iii) The validity of the assumptions upon which different methods are based.

With the help of an experiment Sophocleous (1985) showed that the recharge estimated by using a constant specific yield (ultimate specific yield) may be as high as 300 times the actual recharge. In studies involving applied tracers, it is assumed that moisture movement in the unsaturated zone is controlled by „piston flow" mechanism. However, Sukhija (2003) based on his studies in parts of India showed that preferential flow accounts for nearly 75% in granitic terrains and 33% in consolidated sedimentaries. de Vries and Simmers (2002) caution that that the preferential recharge component can be as high as 90% of the total recharge in a hard rock terrain. Mathematical modelling is a powerful tool, where all the dynamics can be accommodated. However, its accuracy again is dependent on the accuracy of the input parameters. Any estimate is as good as the input data are.

Methods should be chosen based on data availability and study objective. However, it is all-important to understand the principles before applying. Two different methods may yield different recharge rates and still both can be correct (Flint et al, 2002) For example, applied tracer study used to estimate annual recharge rates may correctly represent average conditions over the year, yet be in apparent disagreement with fluxes estimated by applying the chloride mass-balance method, because the latter method may be representing fluxes that were in effect hundreds or even thousands of years ago.

Despite the numerous studies, determination of recharge remains fraught with uncertainty. Because the recharge is estimated indirectly, it is always recommended to use more than one method for reliable estimates. The combination of reliable local data, remote sensing, and GIS technology offers promise for a better understanding and quantification of recharge over large areas (de Vries and Simmers, 2002)

4

Ground Water Resources Assessment at Regional Scale

The scale of resources assessment varies with the purpose for which the study is being taken up. Recharge assessment at the local scale mostly addresses issues at the local level. Regional scale resources assessment on the other hand calculates groundwater budgets of a regional aquifer system/ groundwater basin. Regional groundwater resources assessment is key to the understanding of the sources of water to a groundwater system and how water withdrawals change the components of flows in the hydrologic cycle. A regional ground-water balance is based on the principle of conservation of mass within defined regional ground-water flow system. That is, the amount of water entering the groundwater system plus the amount being removed from storage must balance the amount of water leaving the system over the time scale of interest (Reilly et. al. 2008). Main purpose of the regional scale groundwater resources assessment is the management of the aquifer systems. In this chapter, groundwater resources assessment of few representative regional aquifer systems/ groundwater basins located in varied hydrogeological conditions across the globe have been discussed. A separate section on case studies from different urban areas has also been included. The following case studies are included in this chapter.

1. Kansas High Plains and related aquifers, USA
2. Murray Darling Basin, Australia
3. Dolomite Aquifers, South Africa
4. Regional ground water systems in Ireland
5. Ground water recharge studies in China and Taiwan
6. Urban areas-Seoul, Austin and Perth

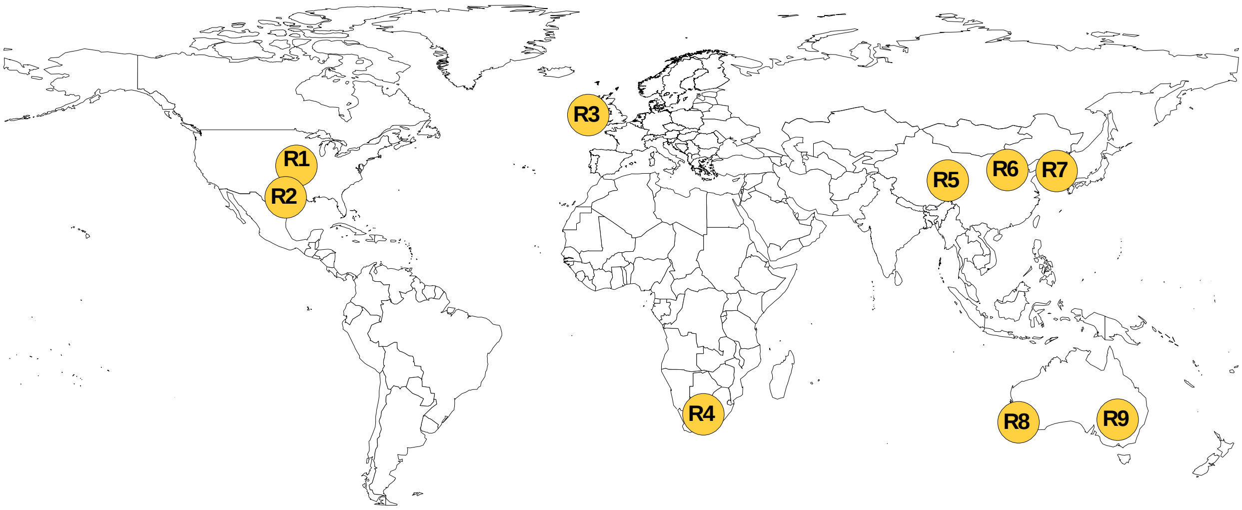


Fig. 4.1: Areas, considered for review of international practices related to regional ground water resource assessments: **R1**: Kansas, USA; **R2**: Austin, Texas; USA; **R3**: Curragh, Ireland; **R4**: Rietpoort South Africa; **R5**: several locations in China; **R6**: Several locations in Taiwan; **R7**: Soul; **R8**: Perth; **R9**: Murray Darling Basin, Australia.

4.1 KANSAS HIGH PLAINS AND RELATED AQUIFERS, USA

Kansas State in USA is characterized by High Plain aquifer which is one of the largest freshwater aquifer systems in the world covering more than 450,000 km^2 in area in parts of eight US states from Texas to South Dakota. It underlies approximately 89,765 km2 covering parts of 46 counties in western and south-central Kansas. The High Plains aquifer is the most important water resource in western and south-central Kansas, an area that lacks extensive surface water and has limited precipitation. It is the source of irrigation water that has transformed a part of the Great Plains into one of the major agricultural regions of the world. About 97 percent of the water pumped from High Plain aquifer is used for irrigation, which accounts for about 30 percent of the groundwater withdrawn for irrigation in the United States (Maupin and Barber, 2005).

Groundwater of this aquifer has been used for irrigation since the 1940s. The estimated recharge is much less than the groundwater withdrawal from the High Plains aquifers in western Kansas, resulting in significant long-term water table declines as well as stream flow declines (Kromm and White, 1992; Sophocleous, 2000a, b; Schloss et al., 2000). Prior to heavy irrigation development, the Arkansas River received base flow from the High Plains aquifer and the connected alluvial deposits. Under these conditions, groundwater naturally flowed towards the river. At the present time, however, the water table has declined below the streambed so that the flowing river may be a recharge source for the underlying sediments.

4.1.1 AQUIFERS

High plain aquifers consist of Pliocene to late Holocene age sediments deposited by eastward-flowing streams and by wind. Depth below land surface to the base of the aquifer is over 500 feet in parts of southwestern Kansas. These sediments consist of unconsolidated clay, silt, sand, and gravel in amounts that vary across the region. Other aquifers are hydraulically connected to the High Plains aquifer. The other aquifers present in the High Plains region include the alluvial, the Dakota, and those within Permian rock units. The aquifer dispositions in High Plain aquifer systems are given in Fig. 4.2.

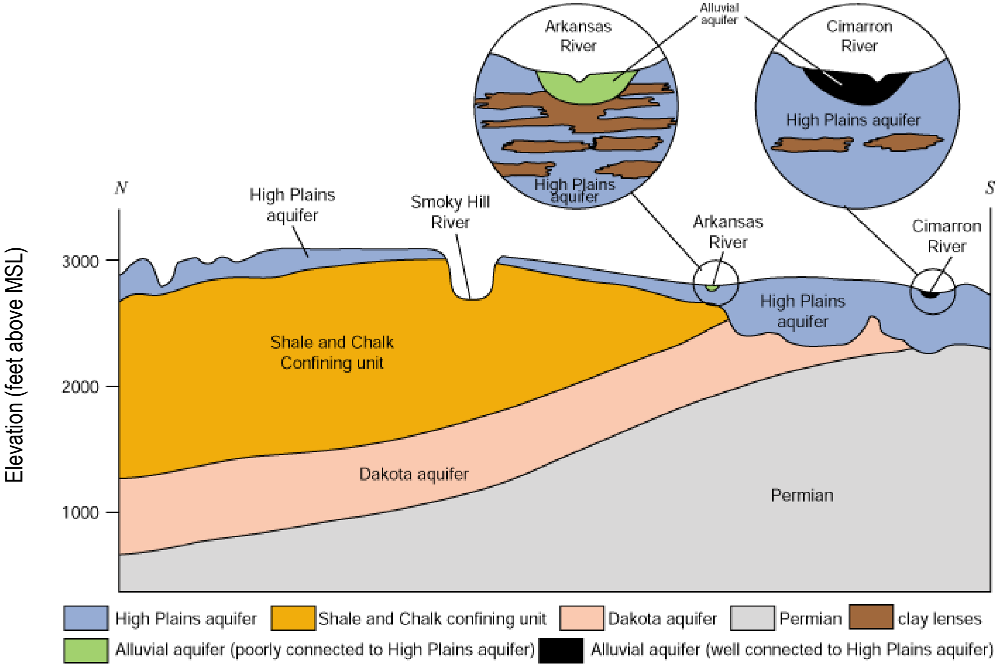


Fig.4.2: Cross-sectional view of the subsurface showing the aquifer distributions in relationship to the High Plains aquifer (Schloss et al., 2000).

4.1.2 GROUNDWATER AVAILABILITY AND ACCESSIBILITY

The Atlas of the High Plain Aquifer in Kansas (2000) provides the basic attributes of the High Plains aquifer, which are useful for understanding the groundwater management policies, adopted in the region. The Saturated Thickness in High Plain Aquifer in Kansas ranges from 0 to more than 550 ft. Map on Change in Saturated Thickness between pre-development (1940-1950) and averaged estimates of 1997-99 indicate that Groundwater Management Districts (GMDs) 2 and 5 in the eastern High Plains show little change, but the Ogallala Districts (1, 3 and 4) have substantial declines.

However, the very large original inventory of groundwater in south-western Kansas makes that area still relatively 'water-rich' in spite of declines, while in other areas, such as west-central Kansas, a much larger proportion of the total aquifer area is now in the marginal (less than 50 feet) or intermediate (50-100 feet) saturated thickness categories. The results show that the absolute changes have been the greatest in south-western Kansas, but because of the large volume of water originally present, the percent changes in that area are not proportionately large. Atlas has projected *Groundwater Storage* map of the region. Groundwater in storage is expressed as = Area x ST x Sy, where, ST is the saturated thickness and Sy is the specific yield. Estimation of groundwater in Storage is followed by graphical presentation of groundwater Availability and Accessibility. *Availability* is the normalized value of *Water in Storage*, presented in categories or intervals. Normalization process involves dividing all values of a particular map by the highest value observed, resulting in a common scale of zero to one. The values used for the availability ranges are: low (0.20-0.0), medium (0.45-0.20), and high (1.0-0.45). *Accessibility* is a measure of how easily water flows through or can be pumped from an aquifer. Mathematically it is the product of hydraulic conductivity and saturated thickness divided by the depth to water. In order to avoid the problems associated with dividing by numbers close to zero, the definition is modified by adding 1.0 to the normalized depth to water. This ensures that the accessibility function will range from 0-1. The accessibility ranges have the same theoretical limit of 1.0, but in practice the observed maximum value for the index was much lower, so the useful numerical values of the ranges are not the same as for availability. For accessibility, the low range is 0.0-0.05, the medium range 0.05-0.19, and the high range is 0.19-0.57 (the maximum value observed). The Atlas contains map of *Estimated Usable Lifetime* which is defined as the number of years remaining until water-level declines reach the level where saturated thickness is 30' -- an approximate value at which large-volume irrigation, municipal, or industrial pumping is likely to be impractical, even though domestic and other low-volume wells can still function if they are completed at the base of the aquifer.

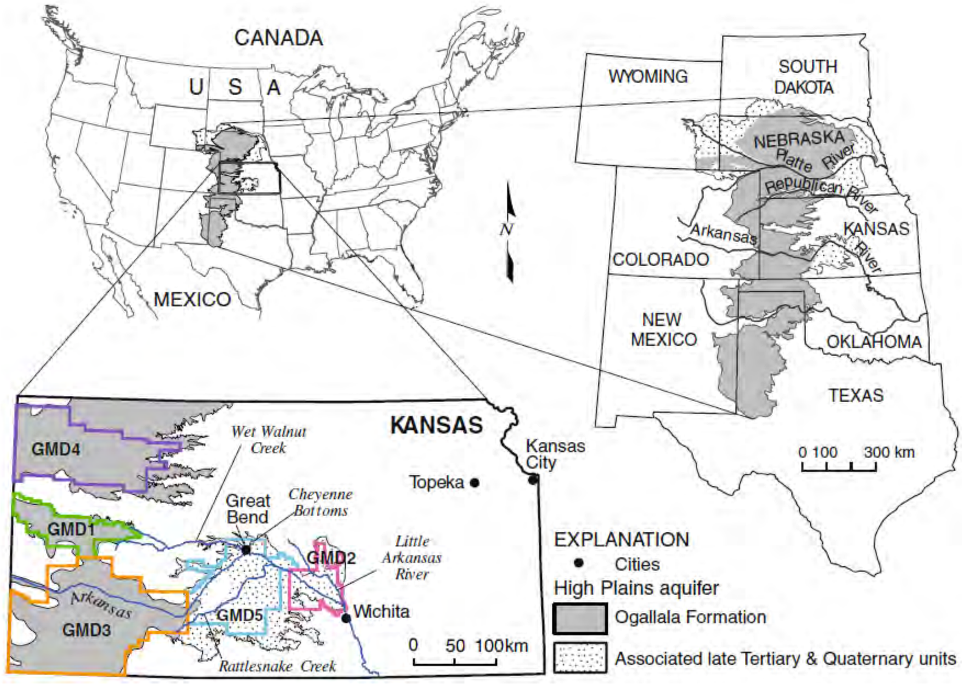


Fig 4.3: Extent of the High Plains aquifer and Kansas Groundwater Management Districts (GMDs) 1–5. (Sophocleous, 2009)

4.1.3 GROUNDWATER MANAGEMENT STRATEGY

Since passage of the 1972 Kansas Groundwater Act, which established local Groundwater Management Districts (GMDs) in Kansas, five GMDs have been formed (Fig.4.3). Each district developed its own distinct management plan with goals to conserve and prolong the life of the aquifer and protect its water quality. The primary goals of agencies involved in groundwater management in these districts are to manage aquifer development according to a designated plan that treats aquifers as either renewable resources („*safe yield*" and „*sustainable yield*" management) or exhaustible resources (*planned-depletion* management). Out of the five GMDs, central Kansas districts i.e. GMD 2 and 5 follow „Safe Yield‟/ „Sustainable Yield‟ policies whereas western Kansas GMDs (1, 3 and 4) follow „Planned Depletion‟ policies (Sophocleus, 2009).

4.1.4 ESTIMATION OF SAFE YIELD

The main techniques that have been used for estimating recharge in the High Plains aquifer in Kansas are Darcy‟s Law, WLF, soil-water budget modeling, base-flow analyses and groundwater modeling. Some of the case studies are enumerated in the following paragraphs.

4.1.5 WATER BUDGET STUDY AT COUNTY-SCALE, 1970

Meyer et al. (1970) conducted a detailed study of recharge from streams, precipitation, return flow from irrigation, and inflow through the aquifers in Finney County, southwest Kansas. They developed a detailed water budget for all of Finney County minus the panhandle area (a total of 24 townships or 552,960 acres) using the following equation:

Total Recharge = Change in Storage + Total Discharge ………….. (4.1)

where all elements of the right-hand side of the equation were observed or estimated, and
Total Discharge = well pumpage + (lateral groundwater outflow − inflow) +StreamflowSeepage.(4.2)

The average recharge during "predevelopment condition" was 0.006 inches/yr. The development-conditions (1940-64) recharge rate was 2.7 inches/yr which probably reflects an additional recharge resulting from recycled groundwater from irrigation and an accompanying increase in effective recharge from precipitation on the irrigated land. Field experiments have indicated an average annual irrigation return contribution of approximately 1 inch/yr.

4.1.6 CLIMATIC SOIL MOISTURE BALANCE STUDIES

Two major regional climatic soil-water balance studies have been recently conducted, one for the state of Kansas as a whole by Hansen, 1991 and the other for the entire High Plains aquifer (Dugan and Zelt, 2000).

USGS study on natural recharge for principal aquifers in Kansas, 1991

Hansen (1991) estimated "potential natural recharge" for the entire state of Kansas. Potential natural recharge refers to the deep percolation rate of soil water (made available from precipitation) below the root zone, which is potentially available to move downwards towards the water table and thereby eventually recharge the aquifer. The soil-water balance simulation procedure employed requires four types of input: 1) monthly precipitation (P), 2) computed monthly potential evapotranspiration (PET) values, 3) hydrologic properties of soils, and 4) vegetation types. The soil-water balance program calculates, on a monthly interval, a variety of outputs such as infiltration, surface runoff, soil-water stored in the root zone, consumptive water use, soil water deficits, actual evapotranspiration, and deep percolation or potential recharge.

USGS study of soil-water conditions in the Great Plains, 2000

Dugan and Zelt (2000) also estimated groundwater recharge using soil moisture balance method applying numerical modelling. They considered the impacts of irrigation on recharge unlike the previous studies in the area. Studies have indicated that deep percolation under irrigated conditions is higher than under non-irrigated conditions except where deep percolation under dry land conditions is large as a result of extensive areas of fallow conditions (Dugan and Zelt, 2000).

4.1.7 REGIONAL GROUNDWATER MODELING STUDIES

Several regional groundwater modelling have been conducted in Kansas or in portions of the High Plains aquifer that include parts of Kansas.

USGS RASA study of the High Plains aquifer, 1986

Groundwater modelling study in High Plain aquifer was taken up in Regional Aquifer System Analysis programme (RASA) conducted by USGS. Luckey et al. (1986) divided the High Plains (HP) aquifer into three segments, the southern HP, the central HP, and the northern HP, and employed a two-dimensional groundwater flow model in each such segment. The numerical model employed was the USGS Trescott et al. (1976) finite difference model using uniform 10-mile × 10-mile (100-mi^2) grid cells. The results of that study are presented for the central HP.

Central High Plains aquifer

The recharge distribution that resulted in the predevelopment (pre-1950) calibration indicated that the overall, the mean, long-term predevelopment recharge rate for the central HP was 0.14 inch/yr. Another 0.0056 inch/yr flowed into the central HP from the southern and northern HP (Luckey et al., 1986).
The development period for the central HP region was considered to be the 1950- 1980 period. Additional stresses on the aquifer during the development period consisted of pumpage, return flow to the aquifer from irrigation, and additional recharge caused by human activities. The simulated change in groundwater storage was 54.9×10^6 ac-ft, whereas the observed change in storage was 50.3×10^6 ac-ft (Luckey et al., 1986).

USGS study of the High Plain aquifer in Oklahoma and adjacent areas, including the High Plain aquifer of south-western Kansas, 1999

One relatively recent USGS study (Luckey and Becker 1999) focuses on the High Plains aquifer in Oklahoma and adjacent areas, and includes the High Plains aquifer of south-western Kansas. A single-layer, two-dimensional MODFLOW model (McDonald and Harbaugh 1988) using a uniform grid-cell size of 1.83-km × 1.83-km (3.35 km^2) was employed. The flow model had an active cell area of 70,479 km^2, including all of south-western Kansas south of the Arkansas River. The model was calibrated for both predevelopment (pre-1946) or steady-state conditions, and development (1946–1997) or transient conditions.

The *Predevelopment*, overall mean simulated recharge from precipitation was about 4 mm/yr.
The total simulated recharge in the *Development-Period* model consists of almost 4 mm/yr background recharge from precipitation, 6 mm/yr due to dry land cultivation, and about 0.5 mm/yr due to irrigation, totalling approximately 10 mm/yr recharge from all sources.

4.1.8 SUSTAINABLE YIELD

The central Kansas GMDs (2 and 5) initially adopted a “Safe-Yield” management plan during the late 1970s and early 1980s, attempting to balance groundwater withdrawals with aquifer recharge. Starting in the early 1990s, GMD2 and GMD5 have moved toward conjunctive stream-aquifer management by amending their safe-yield regulations to include base flow (i.e., the natural groundwater discharge to a stream). Thus the safe yield policy has gradually transformed into sustainable yield policy, though the conventional technique of application of numerical modelling for determination of optimum yield through capture of recharge and discharge has not been applied.

4.1.9 PLANNED DEPLETION POLICY

The three western districts (GMD's 1, 3, and 4) overlie all or parts of the Ogallala aquifer and have the greatest number of large-capacity wells and the highest rate of water-level declines, while having the least precipitation (ranging from west to east from less than 400 to 560 mm/ yr on average) and least ground-water recharge (generally less than 12 mm/yr; Hansen, 1991). Because recharge rates are so low in western Kansas, so-called "safe yield" policies, in which ground-water withdrawals are restricted to average recharge rates, have not been adopted as being too harmful to the region‟s economy. Thus, each of these districts has employed a plan, known as planned depletion policy, which allows a part of the aquifer to be depleted (up to 40%) over a period of 20 to 25 years. However, these western Kansas districts recognized that their long-term goal is to reduce the rate of water use in order to prolong the life of the aquifer and to assure future economic stability in the region. Towards this end, by 1990, GMD 4 had switched to a zero depletion policy, for new wells only. Under zero depletion, an established average water level is maintained, regardless of the recharge rate.

4.1.10 CONCLUSION

In USA, Regional scale assessment of aquifer systems is given very high importance. That is why Regional Aquifer System Analysis is being undertaken at periodical interval in a systematic manner covering the entire country. Groundwater assessment is linked with the groundwater management and the methodology of assessment varies from place to place depending on the hydrogeological conditions and the regional level management policy. The methodologies include Climatic soil moisture balance study, water budgeting and numerical groundwater modelling. The groundwater recharge, groundwater storage and surface-groundwater interaction are estimated based on these methodologies. The policy of Safe/Sustainable yield and Planned Depletion are employed to define the exploitable quantity of groundwater in the region. The strong database and effective regulatory mechanism have enabled in proper assessment and effective management of the resource.

4.2 GROUND WATER RECHARGE STUDIES IN MURRAY DARLING BASIN, AUSTRALIA

Murray Darling Basin (MDB) in Australia is referred to as "Australia‟s food basket" and it has the largest water use for irrigation in Australia. It is described as the Australia‟s most important natural resource. It covers an area of 1.06 million square Km (Fig.4.4). Though this is only 14% of Australia‟s geographical area, MDB accounts for nearly 70% of total irrigated agriculture in Australia. A population close to two million within the basin and one million outside the basin are dependent on the water resources of Murray-Darling basin.

There are four major issues related to ground water in MDB. These are listed below. (MDBC, undated)

i. Land and water salinisation particularly in the Murray Basin and the southern and eastern fractured rock areas. It is estimated that by the year 2040 nearly 13000 square Km area in MDB will be salinised.
ii. On the other hand in the Northern part i.e. in the Darling River basin high variability in surface flow has caused a greater demand for ground water resulting in its overuse.
iii. Wastage of ground water particularly in the Great Artesian Basin, where there are many flowing wells is an issue of concern.
iv. Still there is potential for much greater use of ground water in many parts of MDB.

Figure 4.4: Location of the Murray Darling Basin (shaded)

While in general terms, these issues are primarily associated with particular parts of the Basin, they are by no means confined to them. For example, salinisation is not confined to the Murray Basin and the fractured rocks areas, nor is the wastage of groundwater limited to the Great Artesian Basin.

There are many studies related to ground water assessment and management in Australia. In such attempts, Murray Darling Basin has been the Laboratory in Australia. This section provides a brief review of the different studies related to ground water assessment carried out in MDB.

4.2.1 HYDROGEOLOGY

In Murray Darling basin there are four distinct ground water systems (Fig.4.5)

1. The Great Artesian Basin (GAB)
2. The Murray geological or groundwater basin, known as the Murray Basin
3. The shallow aquifers of the Darling River Basin
4. The local groundwater systems found in areas of fractured rocks

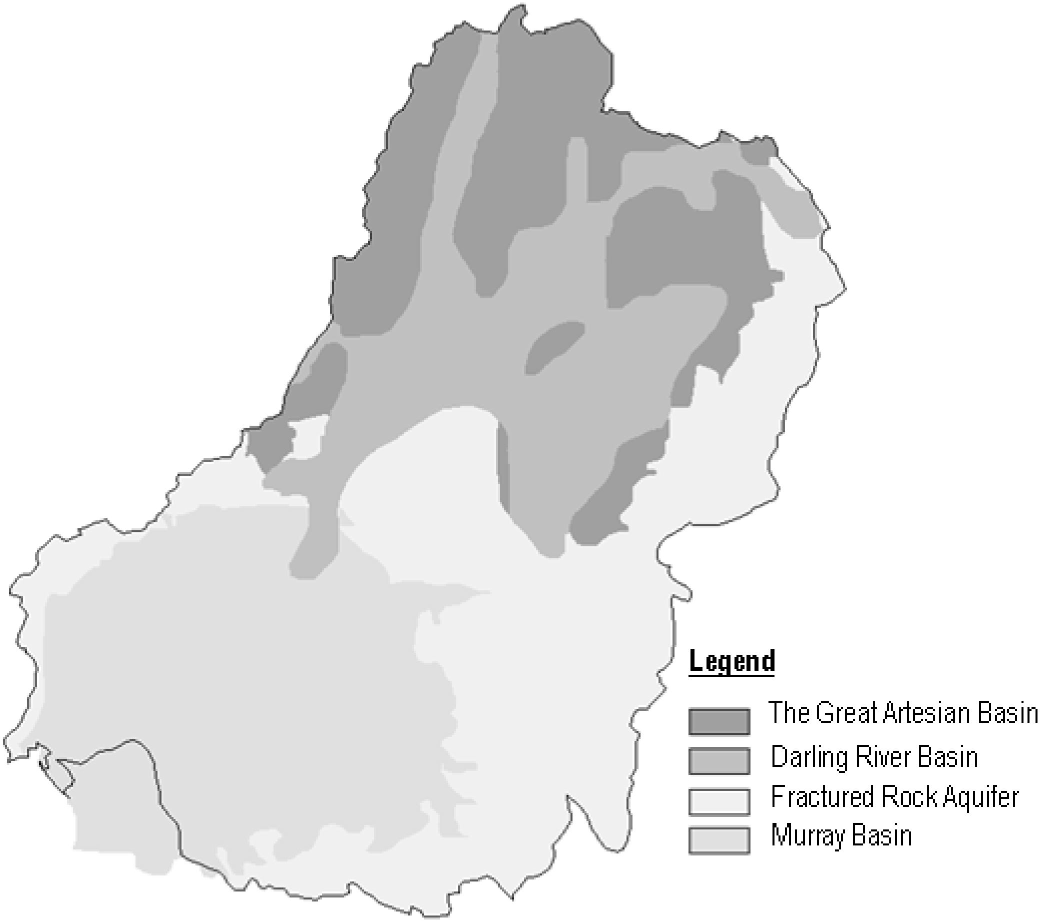


Fig.4.5: Hydrogeological units in Murray Darling Basin, Australia

As figure 4.5 indicates, the boundaries of the groundwater areas do not coincide with those of the Murray-Darling Basin, which is defined on the basis of its surface water resources. The different groundwater regions behave somewhat independently of each other, with only relatively small amounts of groundwater directly interchanged between them. However, water from different aquifer systems is transferred across boundaries as surface water flow.

The Great Artesian Basin (GAB) is one of the largest sedimentary basin aquifer systems in the world, with a total area of over 1.7 million Km^2 (about 22 per cent of Australia) and it extends beyond the Murray Darling Basin. The GAB is a multi-layered confined aquifer system. It consists mainly of two groups of sandstones alternating with siltstones and mudstones, and is up to 3,000 metres thick. The deeper Jurassic aquifer is separated from the Cretaceous aquifer by a thick layer of impermeable mudstone and siltstone

The Murray Basin comprises Cenozoic sediments and sedimentary rocks ranging in thickness from 200 to 600m deposited on a Paleozoic basement.

The Darling River Basin covers nearly 650,000 Km^2 and comprises extensive alluvial fans of Cenozoic age. These fans are made up of sequences of coarse sediments up to 150 to 200 metres thick. Rest part of the MDB is covered with fractured rock aquifers. These areas are characterised by large numbers of small, shallow unconfined groundwater systems, many only a few Km^2 in extent, in marked contrast to the extensive regional aquifers described thus far.

4.2.2 DEEP DRAINAGE ESTIMATION IN THE MURRAY DARLING BASIN

Deep drainage refers to the water that moves below the root zone of the plants whereas recharge is the water that enters the ground water (Pertheram et al., 2000), As such the deep drainage is the higher limit of recharge. Following sub sections provide a short review of deep drainage estimates in Murray Darling Basin. A case study has also been included where details of techniques and field procedures are discussed.

4.2.3 A SHORT REVIEW OF DEEP DRAINAGE ESTIMATES IN MDB

The Queensland Murray Darling Basin (QMDB) covers an area of 260 791 km^2, about 25% of the Murray-Darling Basin, and is Australia‟s largest drainage system. Several ground water recharge estimation studies in Queensland Murray Darling Basin (QMDB) involved application of various techniques like Water Balance, Chloride Tracer, Water Balance Modelling, Tension meters and Bromide Tracers.

Chloride Mass Balance and its variants have been extensively used for estimation of deep drainage in the QMDB. The drainage rates vary with the land use pattern. In Forest land, Steady State balance method for interpreting Chloride gives drainage rate from 0.06 to 01.5 mm/yr whereas in cropped area, Peak Displacement method gives drainage rate from 4.0 to 6.0 mm/yr (Jolly, 1989 and Cook et. al., 2002).

4.2.4 A CASE STUDY ON ESTIMATION OF DEEP DRAINAGE FROM THE QMDB

The objective of this study was to investigate (in the field) deep drainage rates under a range of dry land cropping systems in the QMDB (Tolmie et al., 2004). Chloride mass balance was applied for estimation of deep drainage. Chloride profiles and deep drainage estimates were carried out at thirteen sites in the QMDB. A hydraulic soil-coring rig (Fig. 4.6) was used to take soil samples for chloride (and other chemical) analysis and measurement of field and air-dry soil moisture contents. The studies indicate that deep drainage rates were typically low under native vegetation- averaging 0.3 mm/y and up to 1 mm/y (Fig. 4.7). The drainage rates in the cropped areas are reasonably low (i.e. as a proportion of rainfall) but are considerably higher than that under native vegetation. Drainage averaged about 8 mm/y and ranged from 2 to 16 mm/y. A reasonable amount of this variation is explained by average annual rainfall. Drainage increased with average annual rainfall, being lower at western sites and higher at eastern sites.

Fig 4.6: Hydraulic soil coring rig in operation in Murray Darling Basin (Tolmie et al., 2004)

4.2.5 THE MURRAY DARLING BASIN SUSTAINABLE YIELD PROJECT

The Murray-Darling Basin Sustainable Yield project is the first rigorous attempt worldwide for basin scale assessment of various aspects of water resources. The project is led by the water for a healthy country flagship, a CSIRO (Commonwealth Scientific and Industrial Research Organisation) led research initiative which is set up to deliver the science required for sustainable management of water resources in Australia. The flagship goal was to achieve a tenfold increase in the social, economic and environmental benefits from water by 2025. Major objectives of the MDB sustainable yield project are:

a. Estimation of current and likely future water availability considering
    i. Climate change and other risks
    ii. Surface-ground water interactions
b. Compare the estimated current and future water availability to that required to meet the current levels of extraction use.

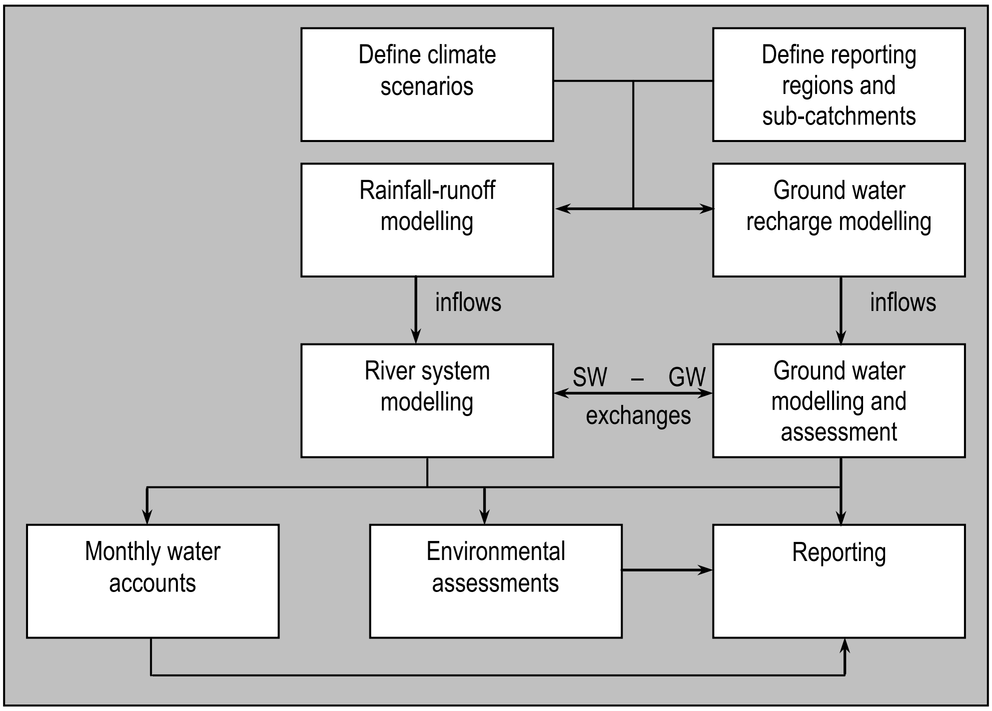


Fig 4.8: Framework for the Murray Darling Basin Sustainable Yields Project (adapted from CSIRO, 2007)

The project is dependent on the cooperative participation of over 15 government and private sector organisations. A broad framework of the project methods is given in Fig. 4.8. A prioritisation scheme (Richardson et al., 2008) was developed which sets the minimum level of effort required to assess each Groundwater Management Unit (GMU) depending on the degree of threat posed by groundwater extraction. In a high priority GMU, the level of extraction is higher than in other GMUs in the MDB, and that extraction is higher than allocation and can significantly impact stream flow. A high priority GMU may also have a high rate of future extraction relative to current extraction. The assessment methods were chosen according to the estimated priority of the GMU (Table 4.1)

Table 4.1: Prioritisation scheme adopted in the MDB Sustainable Yield Project (**Richardson et al., 2008**)

Priority	***Minimum assessment***	***Description of assessment***
Very high	*Very thorough*	*Peer-reviewed model with good monitoring network and good assessment of connection to streams*
High	*Thorough*	*Numerical model with minimal peer review and adequate monitoring*
Medium	*Moderate*	*Minimally calibrated numerical model*
Low	*Simple*	*Simple water balance or analytical approach*

Very Low	*Minimal*	*Description of hydrogeological setting and extraction rates*

4.2.5.1 Diffuse ground water recharge modelling across MDB

Crosbie et al. (2008) reports an attempt to model ground water recharge across the entire MDB. An SVAT (soil-vegetation-atmosphere-transfer) modelling approach was applied for estimating diffuse ground water recharge across the basin. SVAT models are water balance models and simulate the growth of vegetation and the routing of water through the soil zone. They take rainfall (some models include irrigation) as inputs to the land surface and partition this input into evapotranspiration, runoff and recharge, and they are often the preferred method of simulating recharge. The model chosen for the unsaturated zone modelling in this project was WAVES (Zhang and Dawes, 1998). It is a SVAT model that can be used to estimate the components of an unsaturated zone water balance. The WAVES model requires three different data sets: climate, soil and vegetation inputs. A 4 m soil profile was modelled with a free draining lower boundary condition. It was assumed that the deep drainage from the bottom of the model was groundwater recharge and did not become lateral flow.

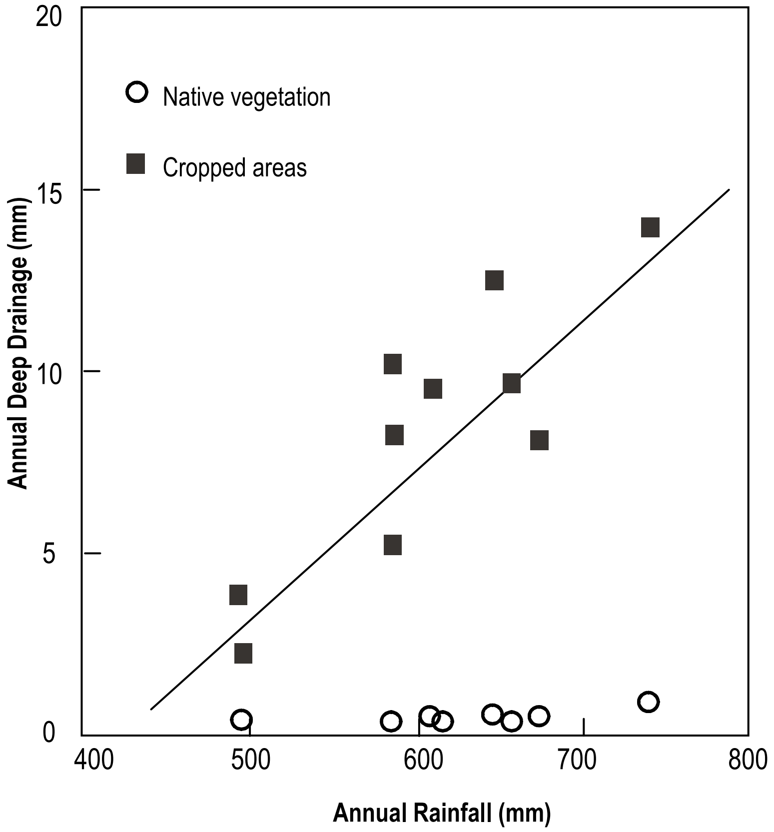


Fig. 4.7: Annual rainfall and annual deep drainage (at 1.5m) in the QMDB area (Tolmie et al., 2004)

4.2.5.2 Other recharge and draft estimates

Recharge estimates

The MDB sustainable yield project involved modelling ground water systems in many river basins. For calibration of these models ground water recharge and ground water abstraction data were used. The ground water recharge data used as inputs to the models are mostly outputs of earlier modelling exercises. Recharge is input to these models as a percentage of rainfall or irrigation.

Ground water draft estimates

Ground water withdrawal in Australia is regulated through volumetric abstraction licenses to the users. Ground water abstractions in many areas are metered. For the Murray Darling Basin Sustainable Yield

Project, ground water draft estimates are mostly based on metered ground water usages. Where the metered data is not complete, draft has been estimated by extrapolating the metered usages.

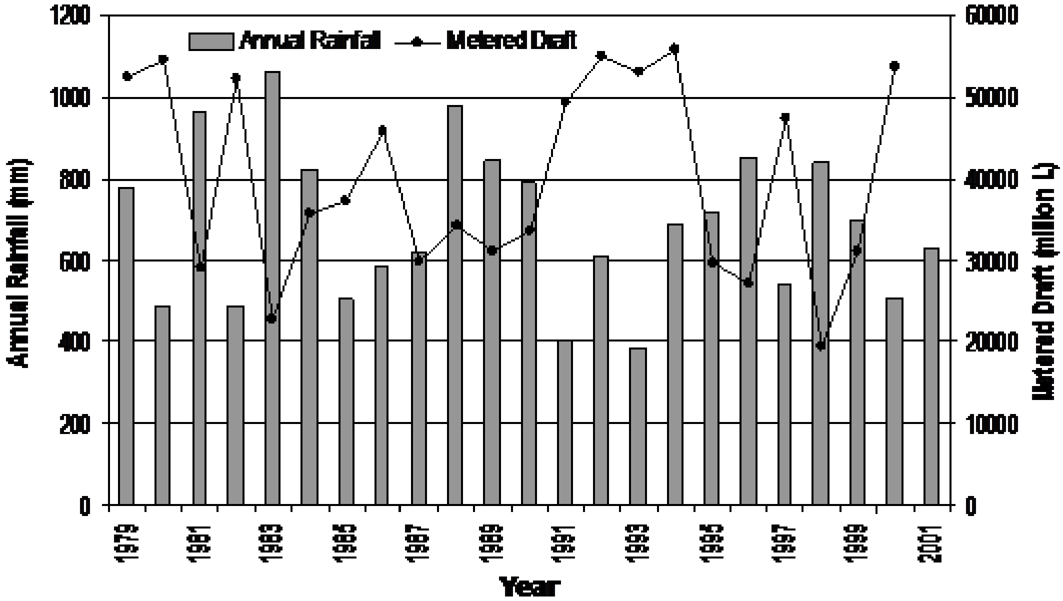


Fig.4.9: Relation between annual rainfall and annual ground water withdrawal in Condamine River Basin (Barnett and Muller, 2008)

As an example, a comparison of annual rainfall and metered annual ground water abstraction in Condamine river basin (Barnett and Muller, 2008) is given in Fig.4.9. The figure shows that in the years of low rainfall, ground water extractions are generally high. Conversely metered groundwater extractions are generally low in years of high rainfall. Metered data has its own limitations in that it may not represent the total volume pumped from the aquifer (i.e. it may not include all extraction sites) **(**Goode and Barnett 2008**)**. Poorer correlation between rainfall and ground water draft, particularly towards the late 1990s (Fig.4.9), may be due to incomplete and/or inaccurate metered use data recording (Barnett and Muller, 2008).

In recognition of the above limitations, following methodologies were used to scale ground water draft data for their incorporation in model calibration. All groundwater bores are scaled such that the modelled groundwater usage equals the best estimates of actual groundwater usage and the annual total of groundwater usage at every bore was distributed into a monthly time series. (Goode and Barnett 2008). In years, or areas, where metered data was not available, groundwater usage was estimated as a percentage of total licensed volume based on a correlation between licensed volume and actual abstractions. Groundwater extraction from the Mid-Murrumbidgee alluvium (Goode and Daamen, 2008) has been estimated in the following way.

a. Town water supply groundwater bores: groundwater extraction = metered usage. The usage is often metered and where not metered were estimated from nearby metered usage.
b. For all other groundwater bores: groundwater extraction was estimated based on access entitlements.

4.2.6 CONCLUSION

Murray Darling Basin provides a typical case study on groundwater management based on Sustainable Yield Policy. The management challenges include issues of varied Hydrogeological setup, surface-groundwater interaction and quality issues in the region. MDB Sustainable Yield Project also highlights the significance of prioritization of assessment unit based on level of extraction for choosing the method for ground water resources assessment.

4.3 GROUND WATER RECHARGE STUDY IN DOLOMITE AQUIFER, SOUTH AFRICA

Recharge studies in South Africa were mostly carried out at a local scale and as part of a larger groundwater resources assessment project. Several studies on ground water recharge estimations were conducted in the dolomite aquifers in South Africa. One case study has been selected to illustrate a comparative analysis of various methods of recharge estimation in hard rock terrains in semi-arid climatic condition.

4.3.1 RIETPOORT DOLOMITE COMPARTMENT

The aquifer comprises of a dolomite compartment (catchment) named the Rietpoort compartment having an area of 70 km^2. The study area is situated about 20 km southwest of Zeerust is shown in Fig. 4.10.

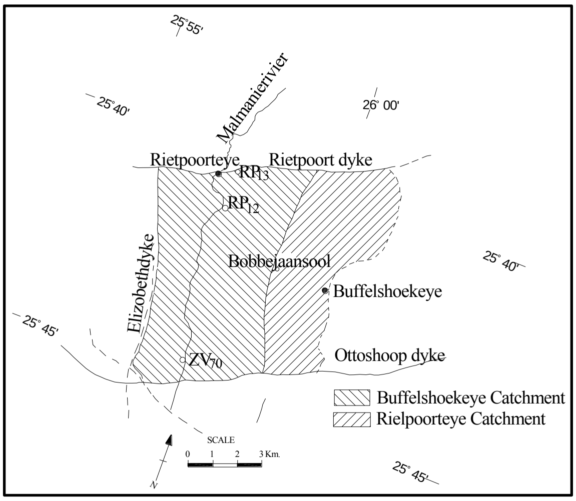


Figure 4.10: Rietpoort Dolomite Compartment

This compartment can be divided into two sub-compartments which are drained by the Buffelshoek and Rietpoort eyes (springs) respectively. The areas of those sub-compartments have been delineated according to their relative flows.

4.3.2 HYDROGEOLOGY

The Rietpoort compartment is part of the Malmani Dolomite Formations which dips eastward under the Transvaal Formation (quartzite and shales). The main aquifer is formed by the Eccles formation which is chert-rich, sustaining high yielding boreholes. The compartment is bounded by a diabase dyke at Ottoshoop to the south and the Elizabeth dyke to the west. To the east, the compartment is bounded by the Pretoria Group of rocks. The Rietpoort spring issues on the contact between the Eccles and Lyttelton Formations, next to the Rietpoort dyke which constitutes the northern boundary. This dyke is presumed to be impermeable but, as will be shown later on, substantial leakage could occur through the dyke.

The Malmani River runs through the middle of the aquifer entering near Ottoshoop in the south and it exits close to where the Rietpoort eye exudes (A3H14). The river is currently dry but some water, mainly from upper springs, is still added from the south.

4.3.3 ESTIMATION OF GROUNDWATER RECHARGE AND STORATIVITY

A variety of techniques have been applied to assess the recharge and storativity of the Rietpoort aquifer viz.

- Saturated volume fluctuation method (SVF)
- Cumulative rainfall departure method (CRD)
- Natural flow of the springs
- Direct parameter estimation method (DPE)
- Chloride method

4.3.3.1 Collation of Data

Water-level and rainfall data were available, and the flows of fountains were obtained from the national hydrological data base for the period 06/1960 till 01/1993. For the next 5 months (until 06/1993) the flow was derived by comparing spring flows to the water-levels in the compartment. The following data were used in water balance studies over the period 08/1977 to 06/1993.

Piezometric levels

Water levels are available for three wells in the area namely RP12, RP13 and ZV70. The similar behaviour of the observation wells can be attributed to inter-connection through leached zones and fractures and similar recharge. The boreholes are not optimally spaced, yet are still suitable for the determination of recharge. The main groundwater flow corresponds with the drainage and is to the north.

Rainfall (Rf)

Rainfall from Ottoshoop was used for at least 90% of the period of investigation. The rest of the rainfall record was constructed using rainfall from station 509/395 (Soekniemeer), station 509/283 (Doornhoek) and 508/649 (Slurry). On average it amounts to about 48 mm/a for the period of investigation and 532 mm for the period since 1944. The rainfall record is stationary.

Abstraction (Q)

Proper pumping records were kept by the municipality but had to be adjusted to obtain reliable monthly values, because of irregular measurements. For the period 1982 to 1993, the abstraction rates remained close to 0.2 x 10^6 m^3/month. Water levels react smoothly during abstraction, because the abstraction rates have remained fairly constant, and the transmissivity of the aquifer is high.

Spring flows

In the water balance calculations the flows of the two springs combined with the abstractions represent the total losses from the aquifer. The flows of the two fountains, issuing from the compartment (A3H009 and A3HO14) have diminished due to the drought, and the latter has stopped flowing because of intensive pumping of wells at the eye. The respective "catchment" areas of the two springs are approximately 30 km^2 and 40 km^2, being delineated according to their average flows. The flow of spring A3H09 known as the Buffelshoek eye stands in a linear relationship to the water-level in the aquifer. The flow data of station A3H14 indicates the influence of flooding from the Malmani River.

4.3.3.2 Saturated Volume Fluctuation Method

The water balance method using an integrated catchment approach, commonly referred to as the Saturated Volume Fluctuation (SVF) Method has been applied. A program compiled by Van Tonder (1992) was used to integrate the water-levels across the total area of the aquifer using a triangular grid of finite elements. The integrated volume fluctuation (SVF) is related to the abstraction and rainfall events, and to the flow of the springs. Integrated values over 12 months, moving one month at a time are used in the water balance interpretations.

The integrated volume calculations are obtained by the PC-programme SVF (Van Tonder, 1992) which also computes the maximum decline in water-level to yield an S value of 0.046 from

$S = Q/dV$…………4.3

Equal Volume Periods

In Equal Volume Periods, the change in the aquifer volume is brought about by the combination of abstraction and recharge as (I-O) is assumed to be constant. Therefore recharge would be equal to the abstraction if the saturated volumes remain constant, or if the ground water over a period of time has returned to the same level.

Using this method, the effective recharge has been estimated as 10% of annual rainfall and amounts to 3.37 x 106 m^3.

Analysis of water level data indicates that after the Rietpoort eye had stopped flowing in March 1984, a steeper decline in water-levels was experienced. Analyzing the data before 05/1983 and after

06/1983, yields values of $S = 0.067$ ($r=0.76$) and $S=0.032$ ($r=0.61$), which if reliable, indicates that the aquifer storativity decreases with depth, as is typical for most aquifers.

4.3.3.3 Cumulative Rainfall Departures (CRD)

Application of the CRD Method is based on the premise that the CRD mimics groundwater Levels and therefore:

$V \propto CRD \Rightarrow V = aCRD + constant$……………………………..4.4

Where, V = Saturated Volume

It can be shown that $\frac{a_1}{S} = a$, where recharge = a_1Rf. The best fit between integrated water level and CRD is obtained at $a = 2.19$. Hence, if $a_1 = 0.10$,

$S = \frac{0.10}{2.19} = 0.046 = 4.6\%$

4.3.3.4 Recharge derived from springflow in relation to the water-levels in the Wondergat

The variations of flows of the Buffetshoek and Rietpoort fountains mimic the water-levels on the aquifer quite well so that the spring flows also relate to the CRD.

Studies have shown that the flows of several of the fountains in the Bo-Molopo area are linearly related to the Wondergat levels, for which records date back to 1922. The Wondergrat is a water-filled sinkhole situated within Wondergat compartment. Regionally there is close correspondence between the Wondergat hydrograph and water level fluctuations in the adjacent compartments. Therefore the flows of springs in the area were corrected according to the Wondergat water-levels, and recharge in relation to the average rainfall was determined.

Recharge

The xy-plot between the flows of the two fountains in relation to the Wondergat levels indicate that the relation with A3H09 (Buffelshoek) is given by (1410.5 + Wondergat level * 48.36) x 10^6 m^3/a which intersects the "magical" Wondergat level of 1410.5 m amsl (Bredenkamp, 1992) at which level the springs should stop flowing due to natural causes. The average flow of the fountain is 1,623 x 10^6 m^3/a yielding an average recharge of 10.2% of the average rainfall of 532 mm/a over the Buffelshoek catchment.

To eliminate the effect of surface flow on measurements of station A3H14 (Rietpoort) it is necessary to obtain the true flow of the fountain during periods when the river has flowed. A range of values was derived to represent base flow conditions and a maximum flow of 1.67 x 10^6 m^3/a was obtained, which conformed to a maximum recharge of 7.8% of the rainfall, however, because of discontinuous data this is not a reliable estimate of recharge. Since the flows for the Rietpoort eye catchment has similar characteristics to that of the Buffleshoek eye, its recharge of 10% of the average rainfall can be used. Thus the recharge calculated for the whole compartment could be set at 10% of rainfall.

4.3.3.5Aapplication of the Direct Parameter Estimation Method (DPEM)

S and RE can be derived using annual data in a linear regression, because the water balance equation reduces to a linear relationship between the change in saturated volumes (dV), abstraction (Q) and rainfall (Rf). Data over a 12-month period (moving at one month increments) are used to compensate for a short-term lag in the water-level response.

In all regressions performed with the DPEM the correlation coefficient never exceeded $r = 0.7$, in spite of having used the all recharge equations. The best fit was obtained based on the rainfall/recharge relationship $RE = aRf\,(Rfi/Rf_{av})$ for the period 06/1983 to 06/1993.

The results are summarized below:

	$RE = aRf(Rf/Rf_{av})$	$RE = aRf$
Storativity	0.034	0.022
Recharge	10.1%	27%
r (Correlation Coefficient)	0.69	0.67

Because of yielding an unrealistic value for RE (27% of Rf) the recharge formula RE=aRf was discarded.

4.3.3.6 Estimation of recharge from Chloride Method

To increase the reliability of the recharge estimate the chloride method has also been applied. The chloride concentration of the groundwater has been analysed and a chloride concentration for the rainfall was inferred from the established regional relationship between rainfall and chloride (0.8 - 1 mg/l). Typical range of chloride concentrations in groundwater is 6 to 7 mg/l.

The recharge according to the chloride method is: RE = 0.9/6.5 = 13.8% of the rainfall, which corresponds well with the value of I4% x Rf, as was computed by way of the equal volume method. To derive the effective recharge, the (I-O) component must be incorporated, yielding an effective recharge of RE = 0.10 x Rf.

The following table summarises the results obtained from the different methods:

Table 4.2: Results of recharge estimation studies in Rietpoort Dolomite Compartment, South Africa

METHOD	RE	S	r	FORMULAE AND OTHER PARAMETERS	COMMENTS
EQUAL VOLUMES	14%=67 mm 10%=48 mm		0.99 0.97	RE = 0.14 Rf RE = 0.10 Rf $=1.35 \times 10^6$ m^3/a	Before 05/1983 After 06/1983
(Q-O)/dV vs Rf		4% 3% 1.9%		1/S = 25-0.037 Rf 1/S = 33-0.056 Rf S = 0.019 $_{e0.05Rf}$ O= 1.35×10^6 m^3/a	S may range between 2% and 5%
Re – O vs dV		3.8% 6.7% 3.2%		O = 1.35×10^6 m^3/a O = 1.35×10^6 m^3/a O = 1.35×10^6 m^3/a	whole period before 05/1983 after 06/1983
CRD	10%	4.6%	0.92	O = 1.35×10^6 m^3/a a = 2.19, k = 1.15 n = 6, m = 60 After 06/1983	RE = 0.10Rf assumed and then solved for S
FOUNTAIN FLOWS	10%			Rfav since 1940 = 532 mm/a	Only Buffelshoek catchment
DPEM	10.1%	3.4%	0.69	$RE = aRf(Rf/Rf_{av})$ after 06/1983	RE equation with best solution
CHLORIDE METHOD	14% 10%			If O = 1.35×10^6 m^3/a	real RE effective RE
SUMMARY (average value)	10%=48 mm	2.5% - 5%		O = 1.35×10^6 m^3/a	

4.3.4 CONCLUSIONS

1) Recharge to the Rietpoort compartment equivalent to 14% of annual rainfall (4.72×10^6m^3/a) applied to the period 08/1977 to 05/1983, but after this date the effective recharge was 10% of Rf_{av} = 480 mm/a. This amounts to 3.37×10^6 m^3/a which still exceeds the current rate of abstraction of 2.8×10^6 m^3/a.

2) As Buffelshoek eye drains part of the catchment at a rate of approximately 1.0 x 10^6 m^3/a, it leaves only 2.37 x 10^6 m^3/a to be abstracted by the six wells in the vicinity of the Rietpoort eye. This is less than the current water requirement of 2.8 x 10^6 m^3/a of Zeerust. If the average rainfall returns to 532 mm/a (which had occurred since 1940), an extra recharge of 0.37 x 10^6 m^3/a would be generated and the current demand will be met.
3) It is not known what effect a lowering in water-level will have on the lateral loss component to the north, as the Rietpoort dyke might become less permeable at depth. The diminished water-levels due to the pumpage may reduce the outflow at the Rietpoort dyke and groundwater from the northern compartment could even be drawn into the Rietpoort compartment.

4) Theoretically lower evapotranspiration losses would occur if water-levels were to drop, which may effectively cause recharge to increase.

5) All indications are that the recharge expressed as a percentage of the rainfall, has declined during the later period of investigation because of diminished lateral inflow, and therefore the resulting I-O is currently negative, due to lower inflow which can be attributed to an increase abstraction in the southern compartments.

4.4 ASSESSMENT OF REGIONAL GROUND WATER SYSTEM IN IRELAND

In the Republic of Ireland, owing to the growing awareness of the importance of groundwater contributions to the environment and, more specifically, to the introduction of the European Water Framework Directive (European Commission 2000), the reliable recharge estimates is recognised as essential to the proper management of the country‟s water resources. Aside from resource issues, recharge assessments are closely linked under the European Water Framework Directive to assessments of groundwater vulnerability, diffuse pollutant loads and protection (safeguard) zones around drinking water supplies.

Ireland is characterized by extensive and thick cover of glacial deposits. The recharge studies in these terrain conditions thus assume unique importance. The bedrock geology of the Republic of Ireland comprises Precambrian to Upper Palaeozoic igneous, metamorphic and sedimentary rocks. The most productive aquifers are found in Carboniferous limestones that underlie approximately one third of the country, mainly lowland areas in the midlands, south and west. These „regionally important‟ aquifers are characterised by secondary permeability that is often enhanced by the processes of karstification and/or dolomitisation. An overburden (termed subsoil in Ireland) of glacial deposits (generally 5–15 m in thickness) covers most of the important bedrock aquifers in Ireland. The glacial deposits are dominated by tills (boulder clays). The matrix of the till deposits generally has a significant content of clay and/or silt and, as such, most of the tills are classified as having a „moderate‟ or „low‟ permeability (hydraulic conductivity). As well as tills, superficial deposits also include fluvial and glacio-fluvial sand and gravel deposits. Where extensive, these deposits can form regionally important aquifers (Misstear et al., 2009a).

4.4.1 GROUND WATER RECHARGE ASSESSMENT IN CURRAGH AQUIFER

The Curragh aquifer is Ireland‟s most extensive gravel aquifer having a surface area of 202 km^2. The Curragh aquifer includes a ground water dependent terrestrial ecosystem, Pollardstown Fen, which is regarded as one of the most important ecological sites of its type in Ireland. In recent years, the hydrogeology of the Curragh aquifer has been investigated in detail in connection with the construction of a road bypass around the main town in the area (Kildare, approximately 35 km southwest from Dublin city). The aquifer extends south-westwards from the town of Naas to approximately 1 km beyond Kildare town (Fig. 4.11) (Misstear et al., 2009b).

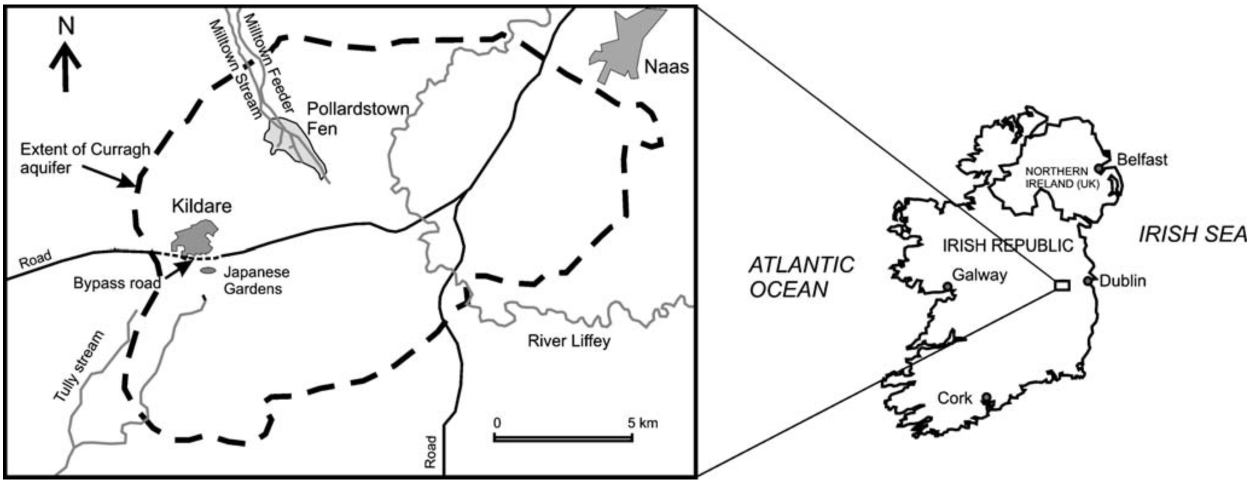


Fig. 4.11: Extent of Curragh aquifer (Misstear et al., 2009b)

The Curragh aquifer consists of glaciofluvial deposits, which were laid down in a trough in the underlying Carboniferous limestone bedrock. These deposits are typically between 20 and 40 m in thickness, with an estimated maximum of thickness of 65 m. Typical of glaciofluvial deposits, the sediment stratigraphy exhibits extensive lateral variability. The Curragh sand and gravel aquifer is generally unconfined, although the presence of clay layers may act locally as confining or semi-confining layers. The sand and gravel around the fen margin was estimated to have permeability (hydraulic conductivity) of around 200 m/day. Additional pumping tests around the fen margin gave permeability values in the range 0.1 to 1 m/day for the clayey gravel deposits, whilst the clays underlying Pollardstown Fen were shown to have a permeability of less than 1 x 10^{-3} m/day. Specific yield was estimated at 0.13. A pumping test undertaken by K.T. Cullen & Co. (to the southwest of Kildare town) prior to the construction of the road resulted in an estimated transmissivity of 650 m^2/day where the aquifer is 20–30 m thick. From these data, permeability was estimated at between 22–33 m/day. The seasonal fluctuations in groundwater level generally range between 0.5 and 2.5 m, the size of fluctuation being related to the location within the aquifer.

Recharge was investigated in the Curragh sand and gravel aquifer using the following approaches: soil moisture budgeting, well hydrograph analysis, numerical groundwater modelling and determination of a catchment water balance.

4.4.1.1 Soil moisture budgeting

As is generally the case, the soil water budgeting method applied in this study did not involve actual measurements of soil moisture. The approach recommended by the Food and Agriculture Organisation of the United Nations (FAO) for calculating crop water requirements, and hence effective rainfall, is the FAO Penman-Monteith method (Allen et al.1998). Prior to the development of the FAO Penman-Monteith method, the Penman-Grindley soil moisture balance method was in common use in both Ireland and the UK.

Such techniques involve the calculation of the soil moisture surplus or deficit from rainfall and potential evapotranspiration (PE) data. The soil moisture budgeting exercise firstly involve the calculation of daily PE values from available climatic data, using FAO Penman-Monteith formula, followed by calculation of Actual Evapotranspiration (AE) and effective rainfall based on these PE values, daily rainfall data and parameters viz. “readily available water” (RAW) and “total available water” (TAW). Long-term rainfall data for this study were available from three meteorological observatories located in the area. RAW and TAW values are obtained from FAO guidelines which provide a range of values for most crops, soil types and climatic conditions. Adopting values (or ranges) that were considered suitable for grassland and mainly sandy loamy soils, under the temperate climatic conditions found in Curragh area, Ireland, gave TAW and RAW ranges of 60–120 mm and 30–60 mm, respectively. In Ireland, AE is typically more than 90% of PE. The average annual effective rainfall for the 30-year period ranged from 321 to 366 mm, respectively. The annual average effective rainfall calculated from the Penman-Grindley (Rushton) soil moisture budget is 334 mm. The main recharge period extends from October to March, but this does include periods of soil moisture deficit in winter that can often extend for several days (Misstear et al., 2009b).

Whilst the application of different soil moisture budgeting techniques was found to result in only small differences in the annual effective rainfall, the estimates of effective rainfall, and hence recharge, are very sensitive to the climate data and other input parameters used in the analysis. The uncertainties involved in the soil moisture budgeting exercise, therefore, highlight the need to also investigate recharge using other approaches, especially approaches that consider the response of the aquifer to recharge.

4.4.1.2 Well hydrograph analysis

In the Curragh sand and gravel aquifer, recharge (R) was estimated as the specific yield S_y multiplied by the change in groundwater level over time (Δt):

$$R = S_y \Delta h / \Delta t \ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.5$$

It is assumed that the well abstractions are small and will have little influence on the analysis and the outflow – inflow to be small. The main difficulty in applying this formula is in having a reliable estimate of aquifer specific yield.

During the construction of the groundwater model for the Kildare bypass project, a value of 13% was assumed for the specific yield of the Curragh aquifer on the basis that the sand and gravel deposit is relatively poorly sorted, containing some fine particles. Applying this single value to the hydrographs for monitoring wells MB2, MB28, MB30, MB31 and MB37 produced a relatively wide range of values for annual recharge, 73.3 mm to 413.4 mm, much larger than the range of effective rainfall determined for the same period by soil moisture balances. This suggests that the value of 0.13 adopted for specific yield is too low. The application of a S_y of 0.19 to wells MB2, MB30 and MB37 gives recharge coefficients in the range of 72–100%, which is considered to be a reasonable range when compared to the results of the catchment water balance (Misstear et al., 2009b).

4.4.1.3 Numerical groundwater modelling

An existing numerical groundwater model was used to investigate the impacts of different recharge inputs (calculated from the FAO Penman-Monteith and the Penman-Grindley methods) on simulated groundwater levels, which were then compared with measured groundwater levels. The existing numerical model (Kildare Aquifer Model or KAM) is based on the public domain MODFLOW code. The model comprises four layers: three sand and gravel layers and one till layer, the layering being necessary to represent conditions that give rise to vertical flows at the fen (Misstear et al., 2009). The KAM operates with two time-steps per month, and so the daily effective rainfall values calculated from the FAO Penman-Monteith and the Penman Grindley approaches were aggregated into 15-day periods. The KAM runs over a 15- year period (1992–2006), and as such could not accommodate the full 30-year dataset compiled for this study. In most of the model area, a recharge coefficient of between 85 and 100% was applied. In a small area west of Pollardstown Fen, where the subsoils are more clayey, some allowance was made for surface runoff, and recharge coefficients were reduced to 33%.

The numerical groundwater model was calibrated using recharge data and for the majority of the dataset, shows a reasonable fit between simulated and observed groundwater levels. Although there are some differences between the modelling results obtained from the Rushton and FAO soil moisture balance approaches, it is important to note that, with recharge coefficients between 85 and 100% for the majority of the aquifer, both methods give groundwater responses that are similar to those measured (Misstear et al., 2009b).

4.4.1.4 Catchment water balance

In the Curragh aquifer, recharge quantities were also estimated by undertaking a water balance of the catchment draining to springs in Pollardstown Fen. Discharges from Pollardstown Fen occur as several large springs and also at numerous seepage zones. A water balance could be obtained by calculating the catchment area contributing to the spring flows and seepages at the fen, the effective rainfall over this area and the fen discharge as measured in the Milltown Feeder canal for the period in question.

The discharge data from the Milltown Feeder canal were incorporated in a simple catchment water balance. Given that:
– The area of aquifer that drains to Pollardstown Fen is 32.2 km^2
– The average discharge from all springs and seepages between March 2002 to May 2005 is estimated as 9,140,088 m^3/year
– The average effective rainfall for the period March 2002 to May 2005 equals 335 mm (FAO method, with higher estimate of AE) and 351 mm (Penman-Grindley (Rushton) method);

Annual average recharge for this 3-year period is estimated to be 284 mm and the recharge coefficient for the catchment lies within the range of 81% (Penman- Grindley) to 85% (FAO, with higher estimate of AE). Applying these recharge coefficient values to the 30-year dataset (1971–2000) of effective rainfall values gives annual average recharge estimates of between 260 and 311 mm (Misstear et al., 2009b).

Summary of the results for the Curragh aquifer is given in Table 4.3.

Table 4.3: Summary of results for the Curragh aquifer (Misstear et al., 2009b)

Approach	Method/ parameter	Determinant	Values
Soil moisture balance	FAO Penman-Monteith	Effective rainfall	321 – 366 mm/year
Soil moisture balance	Penman – Grindley	Effective rainfall	334 mm/year
Hydrograph analysis	$S_y = 0.13$	Recharge co-efficient	40 – 80%
Hydrograph analysis	$S_y = 0.19$	Recharge co-efficient	70 – 100%
Catchment water balance	2002 – 2005	Recharge	284 mm/year
Catchment water balance	2002 – 2005 canal discharge data	Recharge co-efficient	81-85%

4.4.2 CONCLUSION

The case study from Curragh aquifer, Ireland also highlighted the significance of application of multiple techniques for estimation of recharge in an area. It also brought out the fact that all the techniques of recharge estimations are sensitive to the parameters and data elements used in the computation. Slight changes in the parameters result in large changes in the recharge estimates. For estimation of recharge in the aquifers characterized by glacial deposits – SMB, WLF, WB and numerical modelling have been found to be suitable provided the reliable datasets and parameter estimations are available.

4.5 GROUND WATER RECHARGE STUDIES IN CHINA AND TAIWAN

China is the largest country in East Asia. As per the Annual report of the Ministry of Water Resources, Peoples Republic of China for the year 2007-08, China received an average rainfall of 606.3mm in 2007 and the total water resources in China was 2469.6 billion m^3 (includes surface as well as ground water resources) in2007. Explicit estimate of ground water resources are not provided in the said report. The report provides water utilization from different sources showing that out of a total consumption of 578.9 billion m^3 in 2007 surface water accounted for 81.2%, ground water sources and others accounted fro 18.3% and 0.5% respectively. In terms of water management issues there are three major commonalities between India and China (Shah et al., 2004): (i) both India and China are developing countries, (ii) both have perceived need for water sector reform and (iii) in both the countries there are large numbers of diffuse water users. Scanlon et al. (2006) provide a brief review of ground water recharge estimates in China. Information related to methodologies adopted by the govt. agencies to assess ground water resources of China is limited. Resource accessibility is further limited by the fact that most of the relevant documents are in Chinese. The discussions in this chapter are limited to the available recharge estimates by individual researchers or institutions as reflected in the published journal articles.

Taiwan is an island of nearly 36000 Km^2 off the south east coast of China. It is separated from China by the Taiwan Strait. Taiwan‟s most prominent geographic feature is the central mountain range which has more than 200 peaks over 3000m high ad runs for nearly 270 Km. Such high mountains cover nearly 31% are of Taiwan. Hills and terraces occupy another 31%. The rest 38% is alluvial plains.

4.5.1 RECHARGE ESTIMATION CASE STUDIES FROM CHINA

Available recharge estimates in various parts of China are summarized in Table 4.4 and a few representative case studies are presented subsequently.

Table 4.4: Summary of recharge estimate studies in China (Modified after Scanlon et al., 2006)

Sl. No.	**Region**	**Method**	**Precipitation (mm)**	**Recharge rate (mm/year)**	**Reference**
1	Tengger Desert	Lysimeter (Water Balance)	88 – 496 (191)	48	Wang et al., 2004a
2	Shanxi province	Chloride Mass Balance (UZ) CMB (SZ) tritium	550	288 113 48-68	Ruifen and Keqin, 2001
3	North China Plain	Water Balance Model (3 years)	367 (68-482 irrigation)	36-209	Kendy et al., 2003
4	North China Plain	Water Balance Model (52 years)	461 (0-1200 irrigation)	50-1090	Kendy et a., 2004
5	Hebei Plain	Tritium injection	534	92-243	Jin et al., 2000
6	Inner Mongolia	CMB (UZ) CMB (SZ) tritium	360	85 87 40-47	Ruifen and Keqin, 2001
7	Badai Jaran, China (Cold Desert Environment)	CMB	84 mm	1.4 (1 to 3.6)	Gates et al. (2008)
8	Gobi desert (Includes Badai Jaran)	CMB	89 mm	1	Ma et al (2008)

Abbreviations:
CMB (UZ): Chloride Mass Balance (Unsaturated Zone)
CMB (SZ): Chloride Mass Balance (Saturated Zone)

4.5.1.1 Recharge Estimation Studies in the North China Plain

North China Plain (NCP) is the most important agricultural region in China. It has a population of 437 million i.e. 35% of that in entire China (year 2000). Approximately 70% of the land is under cultivation with ground water irrigated winter wheat (Foster et al., 2004). The region is currently experiencing several ground water related problems (Xia et al., 2007).

The climate is continental semiarid with average maximum and minimum temperatures of 46°C and –28°C respectively. Annual average precipitation varies from 500 to 600 mm (Chen, 1999). The four major aquifers in the plain area are

1. *Holocene Formation*: Unconfined, Coarse to fine grained sand with thickness of ~ 60m
2. *Upper Pleistocene*: Shallow confined, Sandy gravels to medium to fine sand, thickness ~60m
3. *Middle Pleistocene*: Confined, sandy gravel to fine sand, more than 90m thick.
4. *Lower Pleistocene*: Cemented sandy gravel with a thin layer of weathered sand

4.5.1.2 Soil Water Balance Studies in North China Plain

Kendy et al. (2003) carried out soil moisture balance studies in Luacheng County, Hebei Province. The study area is underlain by alluvium and reworked loess. Climate data and plant development indicators were measured at the field station. Precipitation was measured daily. Evapotranspiration and soil drainage were measured by lysimeter. Sixteen research sites were established in which wheat for October to June and maize for June to September were cultivated in accordance to the local cropping pattern. Concrete curbs bound each 50m^2 site to prevent run off. Neutron probe access tubes were installed in each site to measure soil moisture changes. Irrigation water was then applied in varied amounts to the different sites.

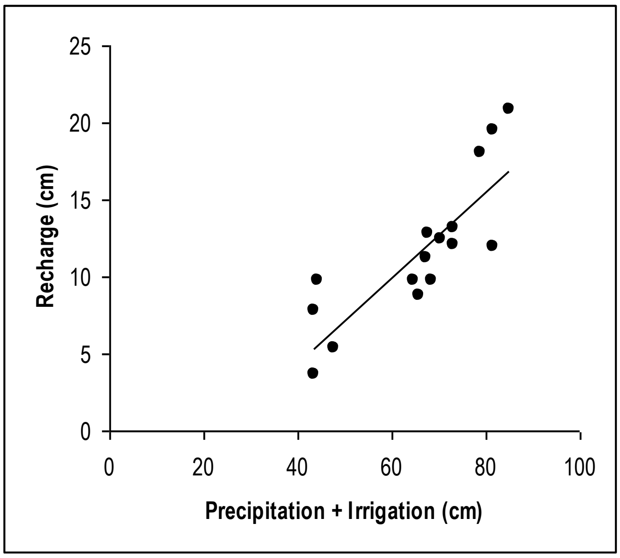


Fig. 4.12: Relationship between precipitaion+Irrigation and the recharge at the study area in Luacheng County

Volumetric irrigation applications were measured directly. Soil moisture content was measured approximately every five days by the neutron probe at 9 to 10 depth intervals between 0 and 180 cm. Mathematical simulation was attempted considering data of three years during the period of 1998-2001 taking 11 soil layers, each layer corresponding to a measure soil moisture interval. Data from four of the 16 sites were used for model calibration and the remaining 12 were used to test the performance of the model. The recharge estimates for the study area are shown in Table 4.5. The study shows that the recharge rates depend not only on precipitation and irrigation, but also on evapotranspiration. Therefore intense rains of the monsoon generated more recharge then did the sum of the smaller precipitation events and irrigated applications during the rest of the year.

Table 4.5: Results of the recharge studies (Kendy et al., 2003)

Site No.	Precipitation + Irrigation (cm)	Recharge (cm)
1	81.6	11.9
2	68.6	9.8
3	65.7	8.8
4	73	12.1
5	81.6	19.5
6	84.9	20.9
7	67.8	12.8
8	78.7	18
9	67.2	11.2
10	73.1	13.2
11	70.5	12.5
12	44.2	9.7
13	47.8	5.4
14	64.5	9.7
15	43.5	3.6
16	43.5	7.8

Kendy et al (2004) in a similar study simulated the historical soil water balance of Luacheng County over a period of 52 years (1919-200) using the calibrated model described by Kendy (2002). Model inputs included basic soil characteristics (saturated hydraulic conductivity, wilting point and effective porosity) and daily crop root depth, leaf area index, precipitation, potential evapotranspiration and irrigation. They found that the recharge rates range from 50 to 1090 mm.

4.5.1.3 Lysimeter Experiments in North China Plain

The study summarized here is based on the large lysimeter located at the Yuchendg Comprehensive Experimental Station, Shandong Province of North China (Yang et al., 2000). It consists of a main body, weighing system, supply-drainage system and data acquisition system. Surface area of the lysimeter is 3.14 m^2 and the interior depth is 5m. Measurement instruments installed in the soil include tensiometers, a neutron probe access tube, thermal sensors and soil water extractors.

The experiment was carried out under natural precipitation and actual surface irrigation. The ground water level within the lysimeter was kept at the same level as that in the surrounding field. The experiment continued for 242 days taking into consideration the different stages of winter wheat. The experiment yielded accurate hourly measurement of water balance components including evapotranspiration and recharge with a mass resolution equivalent to 0.016mm

Wu et al. (1996) used lysimetric experiments and numerical simulation to study the relationship between rainfall and recharge. Four lysimeters were installed in the field at an irrigation experiment station in the Hebei province of North China. The lysimeters were of a constant surface area with a dia of 60 cm but the four had different depths (1.5, 3, 4.5 and 5m). A fixed water table was maintained at the bottom of each soil column. Water fluxes were measured at the bottom of each column daily. To study the relationship between rainfall and recharge to ground water system with deep water tables, a one-dimensional model based on the Richard"s equation simulated soil-water movement in a vertical profile under rainfall infiltration and soil surface evaporation.

Lysimeters and computer simulated data showed that rainfall-recharge relationships are dependent on water table conditions.

1. At shallow water table there is close correspondence between individual rainfall events and the corresponding recharge. The rainfall-recharge relationship here was worked out by a simple regression analysis of measured rainfall and simulated recharge values at the ground water depth (water table) of 1.5 m. The regression equation is $Re=0.87*P - 5.25$, where Re is the recharge by infiltration of an individual rainfall event (mm), P is the precipitation and the constant 5.25 mm is the threshold value of individual rainfall events, below which no recharge reaches the ground water.

2. For intermediate water table depths, the rainfall recharge relationships can be obtained by considering effective precipitation from concentrated rainfall clusters and the corresponding total recharge of an integrated recharge event. Effective precipitation is obtained by subtracting surface evaporation from the precipitation.

3. In the case of a deep ground water table condition, the recharge rate is almost constant so that an average rate of annual recharge can be used to characterize the infiltration to ground water. This means that recharge rates may be estimated by tracers, lysimeters etc.

The two lysimeter experiments described above do not provide annual recharge rates directly, but provide significant insights to the nature of ground water recharge to help working out rainfall recharge relationships.

4.5.1.4 Recharge Studies in Badain Jaran Desert (Cold Desert Environment)

Badain Jaran desert with an area of approximately 49000 Km^2 is the second largest desert in China (Yan et al., 2001). It is located in the western part of Mongolia. Average annual rainfall is less than 100mm. Mean monthly temperatures vary from $-10^{\circ}C$ in January to 25°C in July. The area comprises sparsely vegetated aeolian sand dunes including "mega dunes" upto 400m height. Many interdune areas have ground water fed lakes. The unsaturated zone consists of moderately to well-sorted unconsolidated dune sands. Thickness of unsaturated zone varies for over 400m large dunes to less than 1 m in interdune areas.

Gates et al (2008) report a study from Badain Jaran Desert where ground water recharge was estimated by Chloride Mass Balance Method. A total of 18 profiles ranging in depth from 6 to 16m were studied. Soil samples were collected using a hollow stem augur. Moisture content in the soil samples were determined by gravimetric method. For analysis of chloride, soil moisture was extracted by elutriating 50g of moist sediment with 30ml of deionised water, then centrifuging and filtering (0.45μm). Chloride content n the elutriated samples were analyzed using ion chromatograph. Mean annual precipitation was taken as 84mm based on rainfall measurements in the nearby areas. Data on Chloride in the rainwater was limited. The value of 1.5 mg/l (Ma and Edmunds 2006) was adopted as the best available estimate if Cl^- in rainwater. No data was available from Chloride in dry fall out. Average concentration of chloride in the pore water was taken as 88.7 mg/l, which is the mean of the profiles with low vegetation. With these input values, the average annual recharge was worked out to be 1.4mm/year. Owing to uncertainties in the input parameters, Gates et al. (2008) provide a range of possible recharge values depending on different rainfall and Cl^- concentration scenarios. The recharge rates could vary from 1.0 to 3.6 mm/year, which is 1 to 2% of the average annual rainfall. Gates et al (2008) showed that this recharge rate is one order of magnitude lower than the estimated evaporation from the lakes in the area.

4.5.1.5 Recharge studies in other parts of China

Tengger Desert

Wang et al (2004) studied the impact of vegetation on water balance in the Tengger Desert in China, where revegetation is going on for the last four decades to stabilize the shifting dunes. Based on weighing lysimeter experiments, they showed that the average recharge rate in the non-vegetated areas is nearly 48 mm/year (25% of the annual long term precipitation), whereas in the vegetated areas, the vegetations used all available soil water.

Tritium injection studies in Inner Mongolia and Shanxi Province

Tritium injection studies were carried out by the Ruifen and Keqin (2001) at two sites each in Inner Mongolia and Shanxi Province. The area is covered by carbonate rich loess consisting of predominantly silt sized particles. Annual recharge based on the down ward movement of tritium peak was estimated to be 40 to 47 in Inner Mongolia and 48 to 68 mm in Shanxi Province.

Gobi Desert

Ma et al., 2008 estimated the long term recharge in Gobi Desert from Hexi Corridor to Inner Mongolia Plateau to be 1 mm per year by using chloride mass balance method. Unsaturated zone chloride profiles were taken at three sites in the centre of Badai Jaran Desert. The results of Chloride Mass balance are given in the following table (Table 4.6)

Table 4.6: Recharge estimates from Gobi Desert by Chloride Mass Balance Method (Ma et al., 2008)

Profile	**Sampling interval (m)**	**Mean rainfall (mm)**	**Mean Cl in the rainfall (mg l^{-1})**	Mean Cl in profile **(mg l^{-})**	**Mean Recharge (mm)**
1	0-10	89	1.5	120	1.11
2	0-20	89	1.5	127	1.05
3	0-20	89	1.5	165	0.81

4.5.2 RECHARGE ESTIMATION CASE STUDIES FROM TAIWAN

Information and literature related to ground water recharge estimates in Taiwan are limited. A brief summary of available recharge estimates compiled from the published scientific literature is given in table 4.7. The representative case studies are discussed subsequently.

Table 4.7: Summary of recharge estimate studies in Taiwan

Sl. No.	**Region**	**Method**	**Precipitation (mm/year)**	**Recharge rate**	**Reference**
1	Taiwan	Not specified	-	17.3 billion tons/year	Water Resource Agency (2003) (Lee et al., 2006)
		Water Balance And Base flow analysis	2348	18 billion tons/year (498mm/year)	Lee et al (2006)
2	Pingtung Plain, Taiwan	CMB Mixing Cell Model Site I			Ting et al. (1998)
		Irr+ Ip	2177	676 mm/year	
		Site II	2177	1057 mm/year	
		Site III	2096	316 mm/year	
		Site IV	2237	184 mm/year	
			2219	145 mm/year	
3	Ching Shui watershed	Soil Moisture Budget model	2100	12.4%	Yeh et al. (2007)
		Base flow model		9.92%	
4	Cho-Shui River basin	Recession Curve displacement method	2460	35.1x10^8 t/year (for the mountain regions)	
		Base flow Record estimation	2460	30.9x10^8 t/year (for the mountain regions)	
		Water Budget model	2460	9.9x10^8 t/year (for the plain region)	
		Water balance method simulated by MODFLOW	2460	10.8 x 10^8 t/year (for the plain region)	

4.5.2.1 Pingtung Plain, Taiwan

Pingtung plain is located n the south-western part of Taiwan. Annual average rainfall in the plains is as high as 3130 mm/year (Ting, 1993). Nearly 90% of the rainfall is limited to only five wet months (May to September). The area is bounded on the east by the Central Mountain Range and on the western part by the Kaoping River. The plain is occupied by conglomerates along the western boundary, older coarse alluvium at the mouth of the creeks and remaining part is covered by recent alluvium. Recent alluvium underlies most part of the Pingtung plain.

Ground water over pumping has resulted in declining water levels, sea water intrusion and even land subsidence. Fresh water abstraction for many uses including aquaculture has increased drastically over the years. There is provision for registration of ground water abstraction structure. A Survey by the Chiayi Agricultural Junior College identified 3871 illegal wells in Pingtung County (Lin 1986). As per an estimate (Ting et al., 1998) only 20% of the wells in the coastal area were registered with govt. permits.

Ground water resources of the Pingtung Plain were last assessed in 1961 by the Provincial Groundwater Development Bureau. Recharge was estimated by subtracting average annual run off and evaporation from the total rainfall resulting in an estimate of 903 million m^3 i.e. 14% of rainfall (Hsu 1961).

Subsequently Ting et al (1998) assessed the ground water recharge by Chloride Mass Balance in the area. Methods applied and major findings of this study are described here

Chloride Mass Balance as described elsewhere in this report involves measuring chloride concentrations in the rainfall and that in the groundwater or soil moisture. Ting et al. (1998) used an improvised chloride mass balance procedure by including diffuse recharge component, preferential recharge and recharge from irrigation. In addition to this they also applied a mixing cell model (Gieske and De vries 1990) that takes into account the subsurface inflow or outflow of chloride and water.

The mixing cell model showed that recharge (Table 4.7) to the Pingtung plain is restricted to the areas represented by the sites I and II. The areas represented by the site III and IV show negligible recharge. The estimated recharge rate at site IV, which represents the discharge area near river Kaoping is nearly 7% of the precipitation as against 31% in the area represented by site I. Though this area (represented by site IV) is covered by coarse sand, which allows high inflows from irrigation as well as precipitation, it probably does not contribute to the underlying aquifer because the existing upward hydraulic gradients results in discharge of recharge water through ditches and shallow canals and does not contribute to ground water.

4.5.2.2 Coupled Water Balance and Base Flow Study for Taiwan

Lee et al., 2006 estimated ground water recharge using water balance coupled with base flow record estimation and stable base flow analysis. It is assumed that on long term basis, some of the elements of water balance viz. Change in Storage and net inflow/outflow is negligible on long term basis. Thus the difference between Precipitation and Evapotranspiration emerges as surface runoff and base flow. Coupling the base flow record with water balance, Lee et al (2006) worked out that

Recharge = BFI x (P-ET)……………………………..4.6

Where BFI is the base flow index. Using map based calculations in a GIS environment they estimated long term mean P-ET distribution map. Daily stream flow records were collected for 191 gauging stations spread over Taiwan. Based on daily stream flow records, BFI were calculated. The validated BFI data were then plotted on the map, interpolated using kriging and the grid maps generated. This BFI map was then multiplied with the P-ET in a GIS environment to generate the recharge distribution map. Total ground water recharge thus obtained turned out to be 18 billion tones per year. This value compares well with the long term mean ground water recharge provided by the Water Resource Agency (2003), which are 17.3 billion tones.

4.5.2.3 Cho-Shui River Basin

A recharge event results in an increase in ground water discharge. This is reflected as an upward shift in the stream flow recession curve. The recharge estimation procedure involves determination of the recession index by applying Master Recession Curves (MRC) and then estimating the recharge by employing the following equation

$$R = \frac{2(Q_2 - Q_1)K}{2.3026} \quad \text{………………………………………………..4.7}$$

Where R is the total volume of recharge, Q1 is the ground water discharge at the critical time extrapolated from the pre-event stream flow recession. Q2 is the ground water discharge at the critical time extrapolated from the post-event stream flow recession.

Based on stream flow records of eight stations, ground water recharge estimated by recession curve displacement method turned out to be 120.9cm/year.

Discharge was estimated by stream flow hydrograph separation. The results show that there was 16% difference between ground water recharge and base flow in the mountain area of Cho-Shio River Basin. Chen and Lee (2003) concluded that the loss of water between the areas of recharge and base flow to the streams may be caused by riparian evapotranspiration or could be attributed to recharge to deeper aquifers.

4.5.3 CONCLUSION

Case studies on groundwater resources estimation in China and Taiwan indicate that applicability of a particular technique for recharge estimation depends on the climatic condition of the study area. In Desert areas, CMB method has been applied. Soil Moisture Balance and Tritium studies have been applied in semi-arid main land China while base flow method and Water Budget model techniques have been used for recharge estimation in the hilly and undulating terrain of Taiwan. Lysimetric studies carried out in China demonstrate the applicability of this technique in indirect estimation of groundwater recharge. The case studies carried out in China and Taiwan on recharge estimation would be helpful in providing insight regarding applicability of various techniques under different agro-climatic conditions.

4.6 ESTIMATING GROUND WATER RECHARGE IN URBAN AREAS

As per the estimates of UNCHS (1997), by the year 2030 it is assumed that more than 60% of the world‟s predicted population of 8400 million will live in towns and cities. Much of this increase will be contributed by the developing countries, which accounted for 85% of urban population growth between 1980 and 2000. Many of these cities are ground water dependent. Morris et al. (2003) provide an estimate that over half of the world‟s 23 mega cities rely upon, or make significant use of ground water. Ground water related challenges in these cities are manifold including overexploitation, dwindling water levels, rising water levels, deterioration in water quality etc. Thus identifying various sources of recharge as well as their quantification has become extremely important.

Quantification of recharge in an urban environment is a much bigger challenge than that in a natural or rural environment because of interaction of too many components in an urban area. Lerner (2002) provides a review of techniques and tools for identification of recharge sources and their quantification. In this section case studies of three cities: i. Seoul, South Korea; ii. Austin, Texas; iii. Perth, Australia are discussed.

4.6.1 METROPOLITAN SEOUL AREA, SOUTH KOREA (KIM ET AL, 2001)

While computing the ground water budget four major components were studied and quantified. It showed that the recharge and discharge in a year of average rainfall almost balance each other (Table 4.8). The individual components are described below. Marginal disagreements in the figures are due to rounding off errors in the calculations. A limitation of the study is that it does not consider an important component i.e. base flow to The Han River.

Table 4.8: Ground water budget in metropolitan Seoul, Korea (Kim et al., 2001)

Source of Recharge and Discharge	Recharge amount (m^3/year)	Discharge amount (m^3/year)
Recharge from municipal water supply system	$6.7X10^8$	
Recharge from Precipitation	$4.5X10^7$	
Ground Water withdrawal (domestic and sub-way pumping)		$1.3X10^8$
Ground water inflow to the sewage discharge system		$5.3X10^8$
Total	$7.2X10^8$	$6.6X10^8$

4.6.1.1 Recharge from rainfall

Aquifers in the area are of two types: unconsolidated alluvium of the Han River and its tributaries and fractured rocks (gneiss, schist and granite). The total area (606 Km^2) was divided into several sub domains according to the land-use patterns (Table 4.9). Recharge from precipitation was estimated using recharge ratios (Foster, 1990; Lerner 1990; Van de Ven 1990).

Table 4.9: Recharge from precipitation in metropolitan Seoul, Korea (Kim et al., 2001). Precipitation is taken as 1300mm/year.

Land use	Recharge rate (%)	Area (km^2)	Net recharge (m^3/year)
Rural	6.1	46.7	3.7x10^6
Mountains	15.0	161.4	3.1 x107
Houses	2.9	209.9	7.9 x10^6
Industrial area	2.3	4.4	1.3 x10^5
Schools	3.8	19.1	9.4 x10^5
Roads	0.2	66.1	1.7 x10^5
Rail	3.1	5.7	2.3 x10^5
Other	0.35	92.6	4.2 x10^5
Total		**605.8**	**4.5 x10^7**

4.6.1.2 Recharge from leakage from municipal water system

Seoul has a municipal water supply system of nearly 1.8X10^4 Km, which supplies water from the Han River. The difference between the total volume of water supplied from the Han River and the amount actually recorded as used is attributed to leaks from the system. This leakage is considered to directly contribute to recharge. Cho (1997) estimated the leakage from municipal water supply to be 6.7 X10^8 m^3/year.

4.6.1.3 Ground water withdrawal

Subway pumping: Ground water from the subway systems is constantly pumped out to keep the water table below operation levels. These pumping are metered at some points. Based on sample metered values, Kim et al. (2001) estimate the total subway pumping to be 2.0X10^5 to 2.5X10^5 m^3/day. The annual average turns out to be 8.2X10^7 m^3/year

Pumping for domestic and industrial uses: A total of 16,169 wells are estimated to be in operation in Seoul. The volume of water pumped was estimated by summing up the pumping amount of each well registered in the municipal offices. Thus total ground water pumping is estimated to be 40.6X10^6 m^3/day. The annual pumping turns out to be 4.1X10^7 m^3/year. This pumping volume in practical is an underestimation of the actual pumping because of the presence of large number of non-registered wells (Kim et al., 2001)

4.6.1.4 Ground water discharge into sewage discharge system

Complete sewer system in Seoul has a total length of 9.4X10^3 km. Most of the sewage systems were built more than 20 years ago. Cho 1997 pointed out that numerous sections of the sewer system are broken or cracked. The rate of sewage influx to the treatment plants is 4.8X10^6 m^3/day (Seoul Development Institute 1996) and sewage production of 3.5 million households was estimated to be 3.2X10^6 m^3. The increase in swage volume is attributed to ground water inflow, especially to the large sewage tunnels that lie beneath the water table.

4.6.2 AUSTIN, TEXAS, USA

Austin in Central Texas has a population of 656562 (in 2000). Major aquifer in the city is the Edward Aquifer, one of the most prolific Karstic Aquifers in world along with minor hydrogeologic units within quaternary fluvial deposits. Mean annual precipitation is 813 mm.

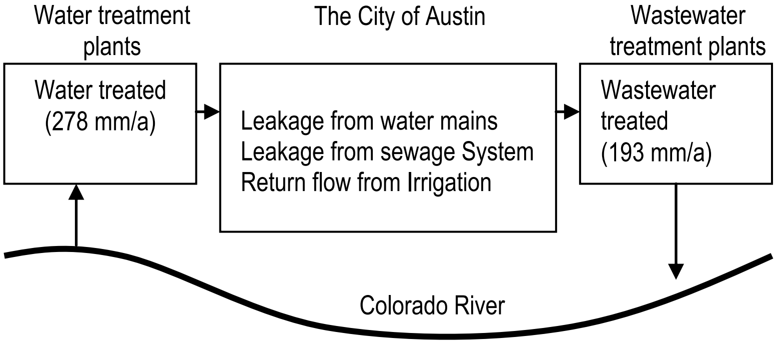


Fig.4.13: Urban excess water in Texas (Garcia-Fresca, 2005)

Direct recharge from

precipitation was estimated by segregating the city area to different aquifer types and amount of impervious cover for the different urban land uses. Each hydrogeologic unit was assigned an infiltration factor (percentage of rainfall). Clays and shale were assigned 0% infiltration rate. Edwards aquifer and quaternary deposits were assigned 8% and 9% respectively. Thus the total direct recharge was estimated as **31mm/a**. During pre urban period, this recharge was estimated in a similar fashion to be **53 mm/a** as the pervious outcrops were higher during that time.

Total indirect recharge from water supply, sewage system, urban irrigation and artificial recharge was considered equal to the „excess urban water‟. This excess urban water in turn is the difference between total water put into the distribution system and the total waster water treated (generated). In the year of the study (2003) in Austin on an average 541000 m^3/d of water from the Colorado River was treated and supplied to the city. On an average 318000 m^3/d waster water was treated in the wastewater plants. This difference turns out to be nearly **85mm/a** of water of exclusively urban origin potentially available for recharge.This excess urban water has the following three components:

i. Leakage from water mains: Water losses in Austin were estimated as the difference between served water and billed consumption. This unaccounted for water turns out to be 12% of water uses. The unaccounted for water can be broken to be „unbilled water‟ (municipal swimming pools, fire fighting, water theft) and „losses‟. These losses account for 7.7% the water treated which amounts to **21mm/a**
ii. Leakage from sewage system: A leakage rate of **10mm/a** was estimated based on the assumption that 5% of wastewater (193mm/a) is leaked through the sewers.
iii. Return flow from irrigation: Out of the total 85mm/a of excess urban water, 21mm/a accounts for leakage from water mains and 10mm/a accounts for leakage from sewer system. This leaves 54 mm/a as infiltration from irrigation of parks and lawns. A part of this - 54mm/a is lost to evapotranspiration. Total plant water requirements were computed from monthly reference evapotranspiration rates for Austin, crop coefficients and allowable plant stress coefficients. The relative contribution of rainfall and irrigation to evapotranspiration was assumed to be equal to their relative proportions. Thus evapotranspiration from irrigation is estimated at 22mm/a and the rest **32mm/a** is estimated as the return flow from irrigation.

Recharge from precipitation during pre-urban periods was 53 mm/a and as a result of additional recharge from various factors operational in an urban area, total recharge in the urban area was enhanced to 94 mm/a. (31+21+10+32).

4.6.3 PERTH AUSTRALIA (APPLEYARD, 1995)

Appleyard (1995) report a study from Perth region, Western Australia with an objective to evaluate impact of sewered urban development on ground water quality and ground water flow regime. These areas are: an uncleared or non-urban area (Barragoon Area), a new residential area (Whitford area; housing less than 20 years old) and an old urban area (Nedlands area, housing about 60 years old). The entire region is covered by Pleistocene Tamala Limestone comprising sand and weak to well lithified calc arenite (20 to 80m thickness) underlain by shale and siltstone.

Ground water age and recharge regime was studied by measuring natural tritium activities in thirty boreholes spread over the region. In non-urban area ground water near the water table showed intermediate tritium values and that at greater depths have low tritium concentration. It shows that the water in the lower part is old (pre 1955). In the new urban area in much of the area ground water near the water table is high in tritium i.e. it is mostly modern water (Post 1955). It suggests that recharge is much greater in this area. In the old urban area also modern water was encountered near the water table at many places. However, the signatures are not very distinct.

The interface between modern and old water in the new urban area facilitated estimation of recharge using the following relation

R=PD/Tr……………………………………………..4.8

Where
R = Recharge rate over time T
P = Total Porosity
D = Depth of tritium interface below water table

T =Time since tritium first entered the aquifer
r =average annual rainfall over time T.

Using these data average recharge in the new urban area was estimated to be 37%. For the non-urban area in this region, average annual recharge is 15 to 25% of the average annual rainfall (Sharma and Craig, 1988; Farrington and Bartle 1988; and Thorpe 1988). This approximate doubling of recharge by urban development is attributed to the clearing of native vegetation, imports of water and infiltration of storm water (Appleyard et al., 1999).

4.6.4 CONCLUSION

Hydrogeology in urban areas is largely influenced by human interference. Groundwater recharge also gets greatly modified. Different chemical and isotopic tracers are applied to identify sources and pathways of recharge. Water balance technique is preferred method for estimation of recharge which is then validated by numerical modelling technique. Case studies from across the globe indicate that recharge from other sources like seepage from water supply & sewers, return flow from irrigation etc is mostly higher than recharge from precipitation.

5

Country Level Assessment

In comparison to site specific studies or regional ground water assessments, country level ground water assessment offers additional challenges especially in terms of data collection and maintaining uniformity and comparability of the results. Country level ground water assessment practices in South Africa, Australia and United States of America (USA) are reviewed in this chapter (Fig.5.1). The procedures adopted in these countries are similar in many respects, yet they have their own distinct attributes.

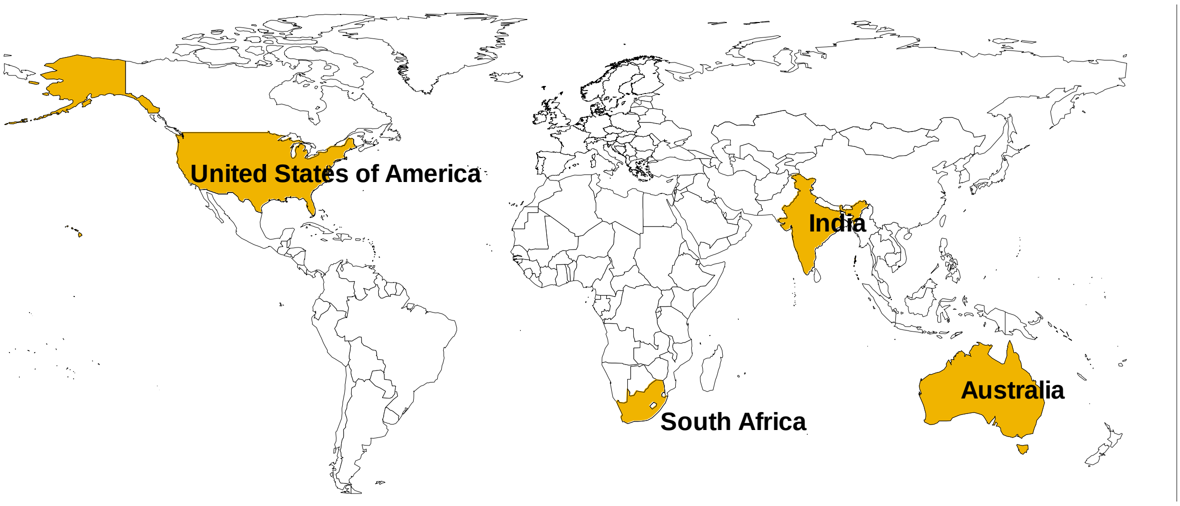


Fig.5.1: Countries (shaded) chosen for review of ground water resource assessment practices

5.1 GROUND WATER RESOURCES ASSESSMENT in SOUTH AFRICA

The procedures for ground water resources assessment in South Africa have been described in various documents. The reports by Bredenkamp et. al. (1995), Xu et. al. (2003) describes the methodologies and case studies at local and regional scale. The official documents of Department of Water Affairs and Forestry (DWAF) (2006) describes the country level estimates of groundwater resources assessment in South Africa.

Table 5.1: Aspects of Ground Water Resources Assessment in South Africa

Key output	**Form of output**
Aquifer Storage	Groundwater storage in m^3 per km^2.
Rainfall Recharge	Mean annual recharge in m^3 per km^2.
Natural Discharge	Mean annual discharge to surface water bodies in m^3 per km^2
Abstraction Potential	Volumes of groundwater in m^3 per km^2 that can be abstracted on a sustainable basis under various constraints (i.e. aquifer permeability, water quality).
Groundwater Use	Average usage in m^3 per quaternary catchment.
Aquifer Classification	Guide on aquifer status to serve as qualitative input into allocating groundwater use

There have been several attempts of assessment of ground water resources of South Africa during last 30 years (Enslin, 1970, Baron et. al. 1998, WSM, 2001). The methodology for assessment of ground water resources has also been revised from time to time. The groundwater resources assessment in South Africa is being presently carried out by the Department of Water Affairs and Forestry under the project named Groundwater Resource Assessment (GRA). There are two phases of the project – Phase I (GRA I) – completed and Phase II (GRA II) – continuing.

In GRA I, National Geohydrological Mapping Programme of South Africa‟s groundwater resources was completed in 2003. A set of 23 Geohydrological Maps (1:500000) were produced.

GRA II is a follow up of GRA I. The key objective of the GRA II project is to provide an approach to quantify groundwater resources in South Africa. Together with the approach the project would provide generic data sets that can be used for rapid and regional scale groundwater resources assessments. The main purpose for quantifying groundwater in the GRA II project is to provide guidance on how much water can be allocated for use. The process for groundwater resource assessment involves the following (Table 5.1). All the Outputs of Groundwater Resource Assessment (GRA) are in GIS formats.

5.1.1 AQUIFER STORAGE

The aquifers are grouped into two broad zones; namely (i) „dynamic‟ storage zone, which is the volume of groundwater available in the zone of natural water level fluctuation and (ii) „Static‟ storage zone, which is the volume of groundwater available in the permeable portion of the aquifer below the zone of water level fluctuation.

The volume of water stored can be estimated as follows –

$$V = \sum AS\Delta h \quad \text{..5.1}$$

Where

A - Area of each grid (i.e. 1 km^2)

S - Storage coefficient / Specific Yield.

Δh - Thickness between any two layers of interest (e.g. WLF, Saturated thickness etc.)

The aquifer thickness for the purpose of estimation of Static Storage is taken as the depth at which the permeability of the aquifer is considered to have decreased substantially from that part of the aquifer which contains the bulk of readily accessible and exploitable groundwater. South Africa has relatively few alluvial aquifers and 90% of the country is underlain by weathered and fractured-rock aquifers. For alluvial aquifers, bedrock is taken as the base of the aquifer. In case of Hard rock terrain, the depth to the base of aquifers is defined as the depth to the water-strike in metres below ground-level (m.bgl).

5.1.1.1 The Estimates

Studies indicate that some 235 x 10^9 m^3 of groundwater may be stored in aquifers in South Africa. It is estimated that 79% of this water is stored in the Weathered Zone (WZ) which is on average only 33m thick, as opposed to an average Fracture Zone (FZ) thickness of 121m – providing a mean aquifer thickness of 154m. The mean storativity of the WZ and FZ is estimated at 2.62 X 10^{-3} and 1.52 X 10^{-4}, respectively. It must be noted that, for various reasons, it is impossible to abstract all this water (DWAF, GRA II, Task 1D, 2006).

5.1.2 GROUNDWATER RECHARGE

Quantification of groundwater recharge is required on a catchment basis for assessing the sustainable use of groundwater, particularly in the context of the National Water Act of 1998. The recharge estimation method to be followed essentially comprises four main components. These components are to generate recharge values, based on

- chloride mass balance (CMB) approach,
- empirical rainfall / recharge relationships,
- a layer model (GIS based) approach and then
- cross calibration of the results with field measurements and detailed catchment studies.

The data processing was carried out on a 1 km by 1 km grid cell size. The final results obtained from the grid modelling were then aggregated up to values at the quaternary catchment scale. The quaternary catchment is the "unit of measure" required by the client. The project also focussed on the calculation of a recharge threshold value (RTV) per quaternary catchment. This is a monthly figure, which indicates the monthly rainfall below which no direct groundwater recharge occurs.

The Estimates

Natural recharge volume has been calculated as 30.52 km^3/a (5.2 % of mean annual precipitation) (DWAF, GRA II, Task 3aE, 2006).

5.1.3 GROUND WATER SURFACE WATER INTERACTIONS

A methodology and algorithms have been developed whereby the effects of groundwater abstraction and its proximity to river channels are incorporated to simulate impacts on base flow. These have been incorporated into a computer programme in an MS-EXCEL environment. These algorithms have also been coded into a multi worksheet MS-EXCEL data base set up by Quaternary catchments and has been used to estimate interactions over parts of the country where base flow occurs. A total of 1382 Quaternaries were simulated out of 1949 catchments in South Africa. These simulations were used to derive relationships between rainfall and potential recharge, base flow and aquifer recharge. Using regressional relationships, Potential recharge and aquifer recharge were extrapolated for the entire country.

The Estimates

As per studies on SW-GW interaction, the Estimated Potential recharge for the country is 27169 Mm^3/a. of this volume, 18818 Mm^3/a contributes to base flow. Estimated aquifer recharge is 17075 Mm^3/a, of which 5254 Mm^3/a generates groundwater base flow. (DWAF, GRA II, Task 3bE, 2006).

5.1.4 ABSTRACTION POTENTIAL

Abstraction potential takes into consideration the factors like groundwater in storage in an aquifer system, the recharge, time span between these recharge events, variable yield potential within and between aquifer systems, current groundwater use, groundwater potability, legal aspects (Reserve) etc. The concepts of resource potential are defined below.

5.1.4.1 Average Groundwater Resource Potential (AGRP)

The AGRP provides an estimate of the maximum volume (m^3) of groundwater that is potentially available for abstraction on an annual basis under pristine aquifer (i.e. no abstraction) and normal rainfall conditions. The AGRP estimates are based on average input values and therefore will not vary dramatically over time as they are based on long-term records (i.e. MAP, average water levels, average aquifer thicknesses etc).

The following basic algorithm is applied to each grid-cell:
AGRP = [Re + (Sv / Di)] – Bf 5.2
Where,
Re = Mean Annual Potential Recharge (m^3 / year)
Sv = Mean Volume of Water stored in Aquifer (m^3)
Di = Drought Index
Bf = Mean Annual contribution to River Base flow

The Drought Index or Di is used to assess the number of years required to bridge cycles of negligible or no aquifer recharge from rainfall, where groundwater abstracted will almost entirely be removed from aquifer storage.

5.1.4.2 Average Groundwater Exploitation Potential (AGEP)

The concept of *AGEP* is based on the fact that it is practically impossible to abstract the volumes the *AGRP* gives since *AGRP* do not capture the rate at which groundwater is transmitted within the aquifer material and therefore it does not give an indication of what can practically be pumped out of an aquifer unit. The rate at which groundwater is transmitted within the aquifer material is, among other factors, governed by hydraulic conductivity or transmissivity of the aquifer systems. However, good information on distributions of hydraulic parameters is as often as not, unavailable. The *AGEP* method attempts to capture the effects of hydraulic conductivity or transmissivity of the aquifer systems indirectly by "recognizing" the good correlation between borehole yield and transmissivity. This is achieved by attaching Exploitation Factors (EF) to borehole yield distributions which are then used to reduce the AGRP values.

The *AGEP*, which is the portion of the AGRP that can practically be abstracted, is defined as follows:

AGEP = AGRP * EF 5.3

5.1.4.3 Potable Groundwater Exploitation Potential

Groundwater quality is one of the main factors restricting the development of available groundwater resources. Water Systems Management (2001) determined the proportion of potable groundwater or Potability Factor (PF) for each Quaternary catchment using total dissolved solids (TDS) and information from Simonic"s (2001) National Groundwater Potability Assessment. Simonic (2001) assessed the potability of the groundwater resources of South Africa, using the DWAFs (1998) water quality standards for domestic consumption in terms of Nitrate, Potassium, Sodium, Sulphate and Calcium concentrations in the water. WSM (2001) took the potable portion of groundwater, as that water that was classified as ideal, good and marginal according to DWAF (1998) domestic water quality standards. Groundwater classified as poor or unacceptable was considered not to be potable.

The Potable Groundwater Exploitation Potential (PGEP) is estimated using the Potability Factor (PF) as follows:

PGEP = AGEP * PF……………...............................5.4

The PGEP is an estimate of the mean annual volume of groundwater available for development for domestic supply purposes.

5.1.4.4 Utilisable Groundwater Exploitation Potential

The volume of water that may be abstracted from a groundwater resource may ultimately be limited by anthropogenic, ecological and/or legislative considerations, which ultimately is a management decision that will reduce the total volume of groundwater available for development – referred to as the Utilisable Groundwater Exploitation Potential (UGEP).

The Utilisable Groundwater Exploitation Potential (UGEP) is derived by replacing the S_v aquifer storage (Eq. 5.2) dataset with the $S_{vr.}$

UGEP = $\{[R_e + (S_{vr} / D_i)] - B_f\} \times$ EF…..............................5.5

Where R_e = Mean Annual Potential Recharge (m^3 / year)
S_{vr} = Mean volume of water stored in aquifer (m^3) that may be abstracted after allowing for the Ecological Reserve
D_i = Drought Index

B_f = Mean Annual contribution to River Base flow
EF = Exploitation Potential

The Basic Human Needs are not estimated separately at this stage, as they are in many cases included within estimates of current annual groundwater use.

The Estimates (DWAF, GRA II, Task 2C, 2006)

A total of 64 groundwater regions of South Africa have been identified based on the type of „openings" (secondary or primary) in the aquifer, lithostratigraphy, physiography and climate.

Table 5.2: Estimates of ground water abstraction potentials in South Africa

Resource Potential	**Parameter/ Factor**	**Estimates**
AGRP	S_V is the volume of water stored in the upper 5m of the aquifer	Normal rainfall conditions - 49.249 x 10^9 m^3/annum; Drought conditions - 41.553 x 10^9 m^3/annum
AGEP	mean EF - 0.40	Normal rainfall conditions - 19.073 x 10^9 m^3/annum; Drought conditions – 16.253 x,109 m^3/annum
PGEP	mean PF - 0.70	Normal rainfall conditions – 14.802 x 10^9 m^3/annum; Drought conditions – 12.626 x 10^9 m^3/annum
UGEP	mean EF - 0.40	Normal rainfall conditions – 10.353 x 10^9 m^3/annum; Drought conditions – 7.536 x 10^9 m^3/annum

AGRP- *Average Groundwater Resource Potential,* **AGEP**- *Average Groundwater Exploitation Potential,* **PGEP**- *Potable Groundwater Exploitation Potential,* **UGEP**- *Utilisable Groundwater Exploitation Potential*

The methodology for estimation of groundwater resource potential has been further improvised and presently in South Africa, **Aquifer Assurance Yield Approach (AAY)** is being used. In this approach, groundwater resource potential is estimated at a designated assurance level or risk level.

5.1.5 GROUNDWATER USE

Groundwater uses in various sectors in South Africa are enumerated in the following table (DWAF, GRA II, Task 5E, 2006).

Table 5.3: Estimates of ground water use in various sectors in South Africa

Sector	**Method Used**	**Data Source Agency**	**Estimate (mcm/a)**
Agriculture: Irrigation	Cropping Pattern method	Irrigation requirements per catchment – WSAM; percentage groundwater dependence - DA Development Survey, Broad Homogenous Agricultural Areas (BHLG).	1137
Agriculture: Livestock watering	Livestock units X 45L X GW Dependence	Livestock units – WSAM; Percentage groundwater dependence - DA Development Survey, Broad Homogenous Agricultural Areas (BHLG).	111
Agriculture:	Assessment of the WARMS	WARMS records	

Sector	Method Used	Data Source Agency	Estimate (mcm/a)
Aquaculture	agriculture information		
Mining	Information provided by mine lease holder	Environmental Management Programme Reports (EMPR) submitted to the Department of Minerals and Energy (DME)	156
Industry	WARMS records	WARMS	65
Rural	Population X percentage groundwater reliance X 25L	Water Services communities data	144
Municipal	Total groundwater use for each Groundwater Dependant town was divided by the municipal population to obtain an average groundwater use per person. This was then multiplied by the projected 2004 population figure.	Information from Regional Hydrogeologists	153
Others			5
TOTAL			**1771**

5.1.6 NATIONAL WATER RESOURCES CLASSIFICATION SYSTEM

National Water Resources Classification System (NWRCS) has been developed under the National Water Act (NWA). It presents an approach to classify ground water resources with the objective to provide a framework for the protection and use of water resources. The NWRCS integrates economic, social and ecological information to recommend a Management Class (MC). The Management Classes (MC) are as follows:

Table 5.4: Ground water management classes in South Africa

Class	Category	Conditions
Class I	Natural	Abstraction<10% of Recharge; No contamination
Class II	Moderately used/ Impacted	Abstraction - 10% to 50% of Recharge; localized contamination
Class III	Heavily used/ Impacted	Abstraction - 50% to 100% of Recharge; localized long-term or widespread short term contamination
Class IV	Unacceptably degraded resource	Abstraction > 100% of Recharge; widespread contamination

The Estimates

Estimates of ground water abstraction w.r.t. recharge in the catchment areas are as follows (DWAF, GRA II, Task 4B, 2006).

In the majority of the country groundwater use is within 80%.
Catchment recording 80-100 % of recharge: C51K – Koffiefontein; D31B – Vanderkloof Dam; B51G – Zebediela; A61E; A23A – Pretoria (east); Q14C; Q30B; J32C; L22C; J24F; J23E; N22A.

Catchments recording Over-abstraction at 100 to 200% : G21B; H10L; H40C; H40F; E21G; D56J; F30F; F30G; F20C; D81E – Onseepkans; D73A – Postmasburg; A63E – Pontdrif; A71A – Polokwane; A71E; B51E; B31E; A24B; B41J – Steelpoort; C23E – Carletonville; Q14A; Q14B – Middelberg; Q44B – Lake Arthur; Q44A; S31E; S31G; N22B; N24A; N14D; L12A; J21E; L22B; L11E; J21A – Beaufort West; J11H.

Catchments recording between 200 and 400%: E23F; D51C; E32E; E32B; F20A; D81G – Pofadder; D42E; A71G – Dendron; A71F; A24C; Q22B; Q30D – Cradock; Q30C; Q12C; N23B; N22E – Waterford; L70B – Steytlerville; N24C – Jansenville; L23B; J21D; J22F; J23B; J23F – Prince Albert; J11D; J11F – Laingsburg.

The highest levels of over abstraction at 400 to 774% mean annual recharge are seen in: D56H; E31F – Loeriesfontein; D82 G, H, J, K; F10A; D82C – Aggeneys; D82B; F30B; D81D; D81A – Augrabies; D53H; D32J; Q21B; Q13C; Q13B; Q30E – Cradock; Q44C; Q50A; N24D – Jansenville; L60B; N24B; N14B – Aberdeen; N14C; N14A; L40A; L23C; L23A; L12B, C, D; J22K; J23A and G.

5.1.7 CONCLUSION

The ground water resources estimation in a countrywide scale is probably most organized in South Africa. Ground Water Resources Assessment is done at periodical intervals. The methodology for estimation has also changed from time to time. The estimation of resources potential takes into consideration the following attributes – recharge, aquifer storage, ease of abstraction of groundwater, potability of water, ecological considerations and confidence level of estimation. Considering the similarities in hydrogeological settings between South Africa and India, some of the relevant attributes, resources estimation procedure followed in South Africa, can be suitably dovetailed in Indian methodology.

5.2 GROUND WATER RESOURCES ASSESSMENT IN AUSTRALIA

Water resources management in Australia has been a big challenge owing to low and highly variable rainfall pattern across the continent. Nearly 80 % area of Australia receives less than 600mm of rainfall per year, and 50% receives less than 300 mm of rainfall per year. Total run off from Australia is an order of magnitude more variable than that from any other continent, whilst the actual runoff is less than a quarter of that from any other continent. As a result of this high variability, Australia needs to follow proper water resources management and store up to seven years‟ worth of water supply (AWR-2005). Australia stores nearly 4 million litres per person or 12 times the average household consumption. Water is stored in 447 large dams and several million farm dams.

Australia has a geographical area of about7.7 million square Km with a population of nearly 20 million. A mere 7% of the land surface is under cropping and only 5% of the populace is involved in agriculture and allied activities. These statistics are in wide contrast to the related figure in India where nearly 1000 million (nearly 50 times that of Australia) people occupy a land of only 3.3 million square Km (nearly 40% of the area of Australia). More than 40% land in India is under cropping and nearly 70% of the entire populace is involved in agriculture and allied activities.

Australia is similar to other developed countries in terms of population and economy, but the per capita agricultural water use in Australia is comparable to developing countries like India and China. Though the focus of water management activities in Australia has mostly been related to surface water resources, it has adopted assessment of sustainable yields for ground water and regulated its allocation and use. A brief account of ground water resources assessment in Australia is provided here.

5.2.1 AGENCIES INVOLVED IN ASSESSMENT AND MANAGEMENT OF GROUND WATER RESOURCES IN AUSTRALIA.

Fig. 5.2: States and territories in Australia

Australia is a democratic federation of six states and two territories (Fig.5.2) united by the common wealth government (federal government). There is a third layer of local government at the municipal (urban) and shire (country) levels. Water is the responsibility of the state and territory governments each having independent water laws and distinct policies. Issues of national significance that concern the commonwealth and all state governments are dealt with by the Council of Australian Governments (COAG). The COAG deals with a wide raft of issues through a number of ministerial councils. The Natural Resources Management Ministerial Council (NRMMC) was formed in 2001 „to promote the conservation and sustainable use of Australia"s natural resources. Within this structure the National Ground Water Committee (NGC) is an intergovernmental network that shares information and provides insight into the national ground water polices, research directions, priorities and programmes.

Recognising the continuing resource issues, the COAG initiated the National Water Initiative (NWI) in 2004 and delegated many responsibilities to the Natural Resources Management Ministerial Council. The NWI is an intergovernmental agreement between federal government and all territorial and state governments to improve management of Australia"s water resources. The National Water Commission is set up to implement the NWI.

5.2.2 UNITS OF WATER RESOURCES ASSESSMENT AND MANGEMENT

Groundwater information is reported at two levels - Groundwater Management Units (GMUs) and Unincorporated Areas (UAs). Both GMUs and UAs are sub-areas of Groundwater Provinces. The ground water management units are defined on the basis of water availability, water use and aquifer characteristics including depth, thickness and salinity. These are the area where ground water development has already occurred or where there is potential for ground water development. GMU is a hydraulically connected groundwater system that is defined and recognised by state and territory agencies. Unincorporated areas include any groundwater resources located outside of the groundwater management units for that jurisdiction. The Unincorporated Areas comprise the areas between the GMUs and the Province boundaries. The GMUs may range from as small as less than 4 km^2 to more than 40 000 km^2.The National Framework for improved Ground Water Management in Australia in 1996 (ARMACANZ, 1996) defined 72 ground water provinces and 538 ground water management units. The Australian Water Resources Assessment (AWRA 2000) reported ground water resources using 538 GMUs, the AWRA (2005) reported 367 GMUs, while the WRON (2006) reported the findings in terms of 355 GMUs. The groundwater management units often overlie each other.

5.2.3 METHODOLOGIES AND FINDINGS OF WATER RESOURCE ASSESSMENTS

A series of water resources assessment were carried out in Australia. Such reports mostly focused on surface water and the available reports mostly summarised data collected from different state and territorial Govts. Major assessments included:

1. A review of Australia"s water resources (1975)-(AWRC, 1976)
2. First National Survey of water use in Australia (1981), (Department of National Development, 1982)
3. A review of Australia"s water resources (AWRC 1987)
4. Water and Australian Economy (AATSE, 1999)
5. Water account for Australia, Australian Bureau of Statistics (2000).
6. National land and water resources audit (NLWRA) 2000-update of AWRC, 1987.
7. Australian Water Resources 2005 (AWR 2005).

AWR 2005, the latest in the above series of publications is an attempt by all Australian Jurisdictions, the WRON Alliance (project consultants) and the National Water Commission (NWC) to compile an authoritative set of data, information and interpretations about the state of Australia‟s water resources as at the commencement of the National Water Initiative (NWI) in 2004-05 as a benchmark to gauge improvements in the quality of water management in Australia as a result of the NWI. Methodologies recommended/followed for some of the ground water resource associated assessments are discussed below.

As a part of the National Water Initiative, the National Water Commission initiated a project for Baseline Assessment of water resources in Australia. Works in the Groundwater Theme involved derivation of the aquifer groundwater balances for the period from July 2004 to June 2005 for the 51 priority Groundwater Management Units (GMUs), which have current groundwater management plans and available data.

5.2.3.1 Derivation of the Water Balance Components: a GIS based Approach

A GIS based approach was followed to derive the water balance components. Key datasets (such as topography, water table elevation, drainage, land use, soils mapping and aquifer properties) are compiled and manipulated as GIS coverages. The outline of the methodology is as follows.

1. Collection and collation of the data available with different agencies
2. GIS derivation of the water balance, based on simplified Darcy‟s flow equations. The algorithm used by MODFLOW numerical ground water flow model code (McDonald and Harbaugh, 1988) is replicated in GIS environment.
3. Incorporation of outputs for the year of assessment derived from existing numerical models, where available. This provides an opportunity to validate the GIS-based estimates.

A brief discussion on the approaches used for estimation of each component of water balance is given here.

Recharge from Rainfall

Rainfall data obtained from the Bureau of Meteorology (BoM) is interpolated to generate rainfall distribution maps for the GMU. The rainfall distributions are compared to the long-term monthly and annual averages to provide a context for how the baseline year compares to rainfall volume.

An empirical model, based on the spatial distribution of factors such as soil type, slope and land use, is implemented within the GIS to provide an initial estimate of recharge distribution across the GMU (based on a variable proportion of rainfall). Alternatively, where the above approach is not feasible, the recharge component is estimated as a residual.

Irrigation Losses

This assessment in the GIS environment involves mapping of irrigation areas and infrastructure (such as channels). The same factors that control the magnitude of infiltration used in the rainfall recharge analysis (e.g. soil type, topography) are applied. The additional flux in these areas due to irrigation loadings is estimated from existing water application data, or indicators (such as land use mapping, crop returns etc).

Lateral Throughflows

Lateral throughflows designate ground water inflow and outflow from the aquifer. As most GMUs do not conform exactly to aquifer boundaries, the lateral flow into and out of an aquifer through the GMUs boundaries is a significant component. The inflows and outflows can be estimated by implementing MODFLOW (McDonald & Harbaugh 1988) solutions to boundary conditions within the GIS. For example, lateral flow can be derived from estimates of aquifer transmissivity and the head gradient across the GMU boundary.

Similarly the vertical leakage between the GMU aquifer and any overlying or underlying aquifers is also estimated. This involves an estimate of the conductance of the geological material between the aquifers (such as clay formations) and the head difference across the boundary.

Surface Water Exchange

The seepage flux between the aquifer and any surface water feature is a significant part of the water balance. Stream losses to (and gains from) the aquifer can be derived within the GIS by mapping the spatial distribution of two factors:

i. The conductance of the geological material defining the rate of movement of water between aquifer and stream, and
ii. The head gradient between the stream stage and the shallow water table, which defines the direction of groundwater movement.

Maps of the stream stage height and the extent of the shallow water table will be used to estimate the seepage direction. Combination of the conductance rating and the seepage direction provides a way of estimating seepage fluxes within the GMU.

Ground water extraction

The model uses actual monitoring data of ground water abstraction collected by the state and territory governments provided such information is available. This data is aggregated both spatially and temporally to integrate with the resolution and time periods used in the overall GIS analysis. Alternatively, where data is not available, extractions are estimated considering the rainfall conditions in the year of assessment and yearly allocations. For example, extractions from stock and domestic bores are usually poorly known. Licenses for these bores normally have allocations between 1 and 2 million litres per year. Depending on whether the year of assessment is determined as being a dry, wet or average year the extractions for each license would be considered to be 2ML, 1ML or 1.5ML respectively.

Evapotranspiration

The rate of evapotranspiration is estimated as a proportion of measured evaporation and is a function of soil type, vegetation type and land use. Daily pan evaporation monitoring is obtained from the Bureau of Meteorology (BoM) and is spatially interpolated across the GMU. The algorithm used for calculating evapotranspiration (McDonald and Harbaugh (1988) estimates of the water table elevation, the ground elevation and extinction depth (which relates to root zone depth) to determine evapotranspiration.

Change in Storage

The change in aquifer storage through time can be estimated in the GIS using a time-invariant aquifer base surface but time-varying hydraulic head surfaces. A uniform storativity value is used or a spatial distribution estimated across the GMU if data is available.

Reporting Scale and Units

For analysis and reporting, ground water management units (GMU) are considered basic units for analysis and reporting. Due to the varying nature of reporting periods for GMUs (such as for groundwater use) annual water balances are estimated. If adequate data is available, it may be possible to provide more frequent water balances (such as seasonal). The standard volumetric unit is the mega litre (ML).

Data availability and reliability

Table 5.4: Reliability assessment of water resource estimation in Australian Capital Territory

Reliability Category	No. of items in this category

A (10%)	15
B (25%)	2
C (50%)	3
D (100%)	2
E (no data)	40
F (currently no data available)	2
Not Applicable	9
Total	73
WMA reliability index*	74%
Water balance error (%)	2%

*WMA reliability index □ $\frac{15\times10+2\times25+3\times50+2\times100+40\times100+2\times100}{73-9}=74\%$

Source: AWR (2007) AWR 2005- A baseline assessment of water resources for the National Water Initiative Level 2 Assessment Water Availability Theme Regional Water Balances, WRON, 449P.

It uses an availability and reliability index to assess the quality of the assessments. Based on qualitative analysis a reliability category is assigned to each dataset. The reliability categories are A (± 10%), B (± 25%), C (± 50%), D (± 100%), E (no data), F (no data currently available) and „not applicable‟. Lesser the percentage, more reliable is the dataset. A 70% reliability index means that on an average the dataset has ± 70% uncertainty. Categories E and F are assumed to have ± 100% reliability index. Category „Not applicable‟ is assumed to have a data reliability index of ± 0%. The WMA (Water Management Area) reliability index is the weighted average of reliability indices of all the items. It is estimated by multiplying the category count by the percentage error for that category and dividing that by the total count minus the number of not applicable items. Water balance error is the total unaccounted flows divided by the total inflows (ground water and surface water). An example for the ACT is given below (Table 5.4).

5.2.3.2 Country Level Assessment of Ground Water Draft

A brief description of the results from an Australian Bureau of Statistics (ABS) project designed to explore a simple method for calculating regional estimates of agricultural water use is given here. The project‟s primary aim was to use a simple methodology to combine the Agricultural Census commodity data with Water Account water use data to produce estimates of agricultural water use at the Statistical Local Area (SLA), river basin and drainage division level. Salient aspects of the methodology are given below (Hawthorne, 2006)

Data Sources and uncertainties

The ABS Agricultural Census is undertaken every five years. The scope of the Agricultural Census is all establishments undertaking agricultural activity with an estimated value of agricultural operations (EVAO) greater than $5,000. The Agricultural Census provides estimates of the area irrigated, in hectares (ha), of a variety of crops down to the Statistical Local Area (SLA) level.

The small area (SLA) data from the Agricultural Census has some known problems. For example in approximately 20% of SLAs the Area of Holding (AOH) for the SLA exceeds the total area of rural land in the SLA. This is due to a number of units on the Agricultural frame whose location address details are not recorded precisely enough to accurately code their geographic location. There are also some large farms, which operate across SLA boundaries and have been coded to the SLA of predominant operations.

Methodology

Step 1: Calculate the mean application rate for State and crop type: The state mean application rate – mega litres (ML) of water per hectare (ha) – can be calculated for each state and crop type. The application rate for each crop applies state-wide.

Step 2: Calculate SLA total agricultural water use: To calculate the total irrigated agricultural water use for a particular crop in an SLA the mean application rate is multiplied by the hectares of the crop within the SLA of interest.

Step 3: Area-weighing to river basins: A Geographic Information System (GIS) such as MapInfo can be used to calculate the area of an SLA that concords to a river basin. This concordance information combined with the SLA estimates from Step 2 can be used to give a river basin estimate of total agricultural water use.

5.2.3.3 The Water 2010 Modelling Approach

The Water 2010 project provides a national coverage of modelled data for surface water runoff and deep drainage to groundwater. Water balance components derived from Water 2010 were given reliability ratings from A to F based on the source of data and the type of analysis the data had undertaken. In general, the Water 2010 data used has a reliability category of C (+/- 50 %)
A national catchment water balance model was developed by the Bureau of Rural Sciences that estimates average monthly and annual evapotranspiration, runoff, drainage, and irrigation demand in one kilometre pixels over the Australian continent and its nearby islands. Outputs are routinely aggregated to river basin level using the 245 basins defined by the Australian Water Resources Council in 1985.

A steady-state catchment water balance modelling approach used. Under this approach, precipitation is equal to total evaporation (soil evaporation and transpiration) plus runoff (as surface and subsurface runoff) and drainage to below the root zone.

$\boldsymbol{P = E + R + D}$………………………5.6

Where P = precipitation, E = actual evapotranspiration, R = surface/ sub-surface runoff, and D = deep drainage.

5.2.3.4 Ground Water Resource Development Ratios and Categories

As part of the National Water Initiative, the national Water Commission has undertaken the Australian Water Resource 2005 (AWR 2005) to prepare a baseline assessment of water resources. The objective of the AWR is to collate data from different jurisdictions in Australia and to provide a snapshot of Australia‟s water resources. AWR 2005 was undertaken by NWC and WRON. It reports on water availability, water use and river and wetland health. In addition to integrating the water availability and use data across Australia, the AWR 2005 also worked out levels of water resources development using the following water resource development ratios.

Table 5.5: Water resource development ratios defined in Australia

Issue	**Ratio**	**Definitions**
Level of use	Total Diversions and extractions as a proportion of total sustainable yield.	$\frac{SW diversions + GW extractions}{SW\ Sustainable\ flow + GW\ sustainable\ yield}$
Consumptive use as a proportion of inflow	Total Diversions and extractions as a proportion of total inflows.	$\frac{SW diversions + GW extractions}{Runoff + GW\ recharge + Water transfers into the system}$
Consumptive use as a proportion of water resources	Total Diversions and extractions as a proportion of total water resources (includes opening	$\frac{SW diversions + GW extractions}{Total Inflows + Water in store at the start of the year}$

	storage volume)

AWR 2005 used a set of nationally consistent ratios. Based on these ratios, the levels of development were categorised (Table 5.6) for the purpose of prioritisation.

Table 5.6: Criteria used to indicate different levels of development and use of water resources (AWR 2005)

Ratio*	**Category**	**Criteria**
Level of Use	Low level of use	<30%
	Moderate level of use	31 to 70%
	High level of use	71 to 100%
	Overused	>100%
Consumptive use as a proportion of inflows	Low	<10%
	Moderate	11 to 30%
	High	>30%
Consumptive use as a proportion of water resources	Low	<10%
	Moderate	11 to 30%
	High	>30%

* Please see table 5.5 for definition of the ratios

Australian Natural Resources Atlas uses the same categorisation (Table 5.7) as described above to provide a simple method to communicate the status of water use.

Table 5.7: Categorisation of ground water management units as per the development status (Australian Natural Resources Atlas)

Category	**Description**
Category–1: Low Development (<30%)	Direct management interventions and information requirement is low
Category–2: Moderately Developed (31 to 70%)	Management and resource information requirement is moderate
Category-3: Highly Developed (71 to 100%)	Require high level of management inputs. Resource information and monitoring is vital for these systems. Development depends on putting in place appropriate water markets to move water to higher value use and to provide surplus for development or environment through efficiency gains.
Category-4: Overused (>100%)	Systems are over-committed in water allocation and/or use-insufficient provision has been made for environmental and non-consumptive uses, management intervention and information requirements are substantial.

5.2.3.5 Sustainable Yield policy and assessment in different states and territories of Australia

The National Ground Water Committee define sustainable ground water yield or sustainable yield as “the ground water extraction regime, measured over a specified planning timeframe, that allows acceptable levels of stress and protects dependent economic, social and environmental values”. In adopting this definition, the NGC provided a few additional guidelines. An abridged version of it is given below.

i. Extraction Regime: It is recognized that a sustainable ground water yield should be expressed in the form of an extraction regime, not just an extraction volume. The extraction limits may be probabilistic and/or conditional.

ii. Acceptable levels of stress: It recognizes the need for trade-offs to determine what is acceptable. How trade-offs are made is a case and site-specific issue and a matter for the individual states to administer. It should take into account interaction between surface and ground water and ground water dependent ecosystems. Precautions must be taken with estimates being lower where there is limited knowledge. Sustainable yields should regularly be reassessed to account for any new information including improved valuation of dependent ecosystems.

iii. Storage Depletion It recognizes that extractions of ground water over any time frame will result in some depletion of ground water storage (reflected in a lowering of the water levels). Where depletion is expected to continue beyond the specific planning time frame, an assessment needs to be made of the likely acceptability of that continuation and whether intervention activity might be necessary to reduce extraction. The major consideration should be „intergenerational equity‟ and a balance between environmental matters.

The definition has been designed to allow for ground water mining. Different states and territories have their own sustainable yield plans. South Australia accepts the notion of controlled depletion on the basis that the ground water is of no benefit if unused. Agricultural Resource Management Council of Australia and New Zealand (ARMACANZ) highlighted the role of community in defining „sustainable yield‟ as follows:

As any definition of sustainable yield embraces a range of technical as well as social, environmental and economic factors, it is necessary for considerable community impact to make judgment of what is sustainable.

Though there is a nationally accepted definition and guiding principle in Australia, there is no common, generalized or standardized method across Australia for the determination of sustainable yield. Most states and territories use their own methods to assess the sustainable yields and levels of development. In some jurisdictions, the sustainable yield concept is not used, and other methods of resource management, such as management to target levels or mining the resource over an agreed timeframe are employed. Sustainable yield generally represents an average level of extraction/diversions over several years. Depending on the level of climate variability and water availability diversions/extractions can be expected to be greater than the sustainable yield in some years and less than sustainable yield in others.

For the purpose of this report the assessment methods adopted by different states and territories in Australia are compiled mostly based on the following two reports:

1. Discovery phase-Australia Water Resources 2005
2. Natural Resource Atlas of Australia

Sustainable yield has been calculated for nearly 97% of the Ground Water Management Units (GMUs) within all states and territories. 59 GMUs have formal Ground Water Management Plans. State Territory and scientific agencies continue to develop and apply methods ad measures for determining sustainable flow regimes (for surface water) and sustainable yield (for ground water). The sustainable yield estimates are not static. For examples the climate has dried during the past decade over much of Southern Australia, so that the sustainable yield derived from the last half of the last century may no longer reflect sustainable levels of extraction.

Ground Water Management regime in Australia considers sustainable yields, ground water dependent ecosystems (GDE), water use and allocation and water quality issues. State/ Territory wise description on these issues is provided hereinafter.

1. Australian Capital Territory (ACT)

Sustainable yield has been calculated for all sub-catchments, using a percentage of mean annual recharge. Ground water information is limited and is based largely on modelling of ground water and surface water interactions. A linear relationship between annual rainfall and rates of recharge has been assumed. Sustainable yield estimates are based on a water balance method. This included provision for evapotranspiration, aquifer through flow, leakage from one aquifer to the other and surface water interaction. Ground water abstraction is limited to 10% of average annual recharge. This is in line with the „precautionary Principle‟.

Water use in ACT is metered and allocation is based on sustainable yield. No Ground Water Dependent Ecosystem (GDE) is identified within ACT. The interaction between surface water-ground water systems is acknowledged within all management plans with the assumption of a 100% connection.

2. New South Wales (NSW)

Recharge to ground water has been estimated considering two components: Recharge from rainfall and recharge from river. Rainfall recharge was calculated according to assessed rainfall, area and proportion of rainfall accessing the aquifer (rainfall infiltration factor). River recharge was estimated using a modified form of the Darcy equation. An additional factor was applied as the „fraction of the year" and the „fraction of river reach" that is considered a losing stream. Through flow, underflow, irrigation returns etc. have not been considered. Numerical models are available for the „big 6" GMUs which are over allocated or over used.

As a default 70% of the annual average recharge is considered sustainable. Ground Water Dependent Ecosystems (GDE) are recognized in all GMUs with high priority areas identified. The interaction between surface water and ground water is recognized in most of the GMUs with the rest being assessed though all GMUs are considered connected unless proven otherwise. New South Wales proposes to move away from separated surface and ground water plans to single water resource plans. Allocation based on sustainable yield less basic rights, environmental, town water supplies, aquifer interference and indigenous water. Some GMUs have annual announced allocation depending on ground water levels. Ground Water extraction is metered and priority GMUs have meters read at least twice a year.

3. Northern Territory (NT)

For estimation of aquifer recharge, the Northern Territory is divided into four zones based on likely dominant mechanism of recharge. The recharge mechanisms are broadly based on rainfall pattern of the Northern Territory from the northern top end to the southern desert area. Within these zones the probable recharge rates range from 0.2 to 5 ML/Ha/Year in the northern most zone to 0.02 to 2.5 ML/Ha/Year in the southern most zone.

For the Ground Water management Units within the Northern Territory, sustainable yield has been defined as the ground water extraction regime, measured over a specified planning timeframe which allows acceptable levels of stress ad protects dependent economic, social and environmental values. For unincorporated areas the sustainable yield has been defined as 50% of the average annual aquifer recharge.

In the GMUs, ground water use data is based on estimates and metering. In the unincorporated area, use is calculated based on the number of bores, land use and assumed consumption rates. Only few GMUs recognize GDEs, but there is no formal method established to identify the water requirements for GDEs. At present there is no management plan that recognizes surface water- ground water interactions.

4. Queensland

In Queensland sustainable yield is calculated for almost all the GMUs. A variety of hydrogeological methods including hydrograph response, modelling and water balance methods have been used. The sustainable yield figures represent the aquifer yield over a long-term critical period. It takes into account aquifer response to changes in storage, which are use, recharge, inflow and outflow. Recently in the water allocation management programme sustainable yield is now defined as the „ground water extraction regime" measured over a specified planning timeframe and that allows acceptable levels of stress and protects the higher value uses associated with the total resource. The assessment is regarding an extraction regime, not just an extraction volume.

Ground water dependent ecosystems have been identified in some of the GMUs, but there is no formal allocation of water to them. The interaction between surface water and ground water system is being acknowledged in a few ground water management plans. Ground water use is determined through metering.

5. South Australia (SA)

South Australia uses a system of Proscribed Areas (PAs) instead of ground water management units (GMU). 70% of the PAs have management plans. Sustainable yield in South Australia is determined by the rate at which ground water can be pumped without causing long-term decline of potentiometric surface (or water table) or undesirable effects-such as salinity increase.

For sedimentary aquifers, where abstraction data exists, sustainable yield has been determined using water level, salinity and metered use records in combination with recharge analysis involving rainfall recharge estimates, lateral throughflow estimation, chloride analysis and numerical modelling. For the hard rock terrains, data availability is poor and the numerical values given for sustainable yield are mostly based on estimated abstraction or educated guess.

Mining of ground water has been included in the sustainable yield estimate for the unconfined aquifer of the Mallee. Present resultant decline in water level is 5cm/year averaged over the whole region. This policy of controlled mining for irrigation extraction is forecast to deplete the resources by up to 15% over the next 300 years. In some parts of the Great Artesian Basin, ground water abstraction is subject to restrictions including drawdown limits, which ensure the protection of ecologically significant mound springs nearby.

Ground water dependent ecosystems and surface water-ground water interactions have been identified in most of the PAs. Two PAs have their entitlements capped (Further increase in entitlements for ground water abstraction is banned). Water use data is available for 75% of the PAs. For most of these PAs, abstraction is metered, while for the rest, an area based approach is followed to calculate use.

6. Tasmania

Sustainable yield for each GMU and unincorporated area (UA) was set at the average annual recharge to the aquifer. The estimation of recharge was based on a percentage of the area weighted average rainfall volume. For the two GMUs comprising beach sand deposits, annual recharge was estimated at 30% of rainfall. For the rest of the GMUs and all the UAs recharge was assigned 3% of rainfall.

None of the GMUs have formal management plans. Ground water dependent ecosystems are identified in most of the GMUs. There has been no assessment of ground water-surface water interactions. There is no ground water licensing system. Ground water use data for some specific areas are compiled through water users‟ surveys.

7. Victoria

Sustainable yield estimation methodology varies across the state according to the aquifer characteristics. In most of the cases the sustainable yield has been determined as a percentage of rainfall with adjustments made to take into account environmental requirements. When resource commitments in a GMU reach 70% of the estimated sustainable yield, the area is declared a ground water supply protection area.

Few GMUs have formal ground water management plans. Ground water depended ecosystems and surface water ground water interactions are recognized only in case of few GMUs. Ground water use is metered in nearly 30% of the GMUs. For the rest ground water use is based on estimates.

8. Western Australia

Renewable ground water resource was determined from the area of land surface or aquifer multiplied by the mean annual rainfall and the applicable recharge factor for each defined area. Recharge factors for Perth division were derived from existing management plans. For the remainder of the state, they were either derived from ground water investigations or were estimated by reference to other areas and consideration of rainfall, topography and aquifer type. Sustainable yields are based on results derived from existing ground water area allocation plans, water management plans or on the outcomes of long term monitoring of ground water levels within an aquifer and associated abstraction volumes. In the GMUs where sufficient data is not available, the sustainable yield for each was given by the renewable ground water resource minus as allowance for wetlands and where appropriate, for seawater intrusion.

Major uses are metered but other use is monitored through water use surveys.

5.2.4 CONCLUSION

Like USA, the definition of Sustainable Yield Policy in Australia varies from State to State. The Assessment units are mostly Ground Water Management Units (GMUs). Rest of the area are „unincorporated area". Groundwater balance is estimated through a number of methods thereby decreasing the uncertainty in the estimation. The system of licensing of groundwater extraction units facilitate in better estimation of groundwater withdrawal. Three types of categorization based on level of utilization vis-à-vis water resources availability enable analysis of the groundwater situation in the assessment area from different perspectives. Finally the „Reliability Assessment" provides a systematic arithmetic tool to estimate the confidence level of the assessment.

5.3 GROUND WATER ASSESSMENT IN UNITED STATES OF AMERICA

During the past century, several ground water assessments have been completed by the U.S. Geological Survey (USGS) on a national scale. The first of these assessments was completed by O.E. Meinzer (1923). Several decades later Meinzer's publication was followed by State-by-State summaries on ground-water resources (McGuinness, 1951 and 1963); summary appraisals for 21 regions of the Nation in the 1970s (U.S. Geological Survey Professional Papers 813A-U); State-by-State summary (U.S. Geological Survey, 1985); and by the Regional Aquifer-System Analysis (RASA) Program in which 25 of the Nation's most important regional ground-water systems were evaluated (Sun and Johnston, 1994).

5.3.1 MAJOR AQUIFERS IN USA

The areal and vertical location of the major aquifers is fundamental to the determination of ground water availability for the Nation. Hence, in United States, the ground water resources assessments are aquifer based. Analysis of ground water flow systems in the major aquifers formed the basis of the National Scale assessment.

The location, hydrologic characteristics, and geologic characteristics of the principal aquifer throughout the 50 States, Puerto Rico, and the U.S. Virgin Islands are described in the Ground Water Atlas of the United States (Miller, 2000; *http://capp.water.usgs.gov/gwa/*). A two dimensional map indicating 63 principal aquifers on a national scale is derived from the Ground Water Atlas of the United States (U.S. Geological Survey, 2003). Although the map is two dimensional, it provides a useful visual representation of the Nation's complex three-dimensional ground-water resource.

In some places, other productive aquifers underlie those shown on the map. For example, the highly productive limestone that forms the Florien aquifer system of the south-eastern United States underlies the entire Florida Peninsula and extends into Georgia, Alabama, and South Carolina. Only small areas of this aquifer system are shown on the map, because it is covered in many places by younger sand aquifers. Likewise, some aquifers in sedimentary rocks are overlain by confining units and extend into the subsurface beyond the areas shown on the map. Some of the principal aquifers are systems of multiple aquifers. For example, the :Northern Atlantic Coastal Plain aquifer system" is identified on the national map as a principal aquifer composed of semi-consolidated sand that is present in several States, including southern New Jersey. At a regional level, however the "Northern Atlantic Coastal Plain aquifer system" is actually a system of aquifers and confining units.

5.3.2 REGIONAL AQUIFER SYSTEM ANALYSIS (RASA) PROGRAMME (USGS)

The Regional Aquifer-System Analysis (RASA) Program began in response to the 1977 drought and recommendations by the U.S. National Water Commission and the U.S. Comptroller General. From 1978 to 1995, 25 of the Nation"s most important ground-water systems were evaluated as part of the RASA Program. Computer models were used to develop estimates of current and future water availability for many of these systems. In addition, the Ground-Water Atlas of the United States (Miller, 2000; http://capp.water.usgs.gov/gwa/) was compiled as a general source of information on ground-water resources. The RASA Program provided a baseline of knowledge on the aquifer systems studied that proved useful for assessment and management of ground water resources.

5.3.3 GROUNDWATER RECHARGE IN UNITED STATES

For the purpose of groundwater recharge estimation in United States, recharge processes have been segregated into two types - diffuse recharge and localized recharge. Diffuse recharge refers to infiltration of precipitation. Localised recharge, on the other hand, refers to recharge from surface water bodies to the ground water system.

In United States, average precipitation map have been prepared which is useful in determining broad areas of potential high and low recharge.

The amount of water available for natural recharge to the ground water system and as surface runoff to steams is represented by the amount of precipitation minus the amount of evapotranspiration. It is estimated that evapotranspiration for the conterminous Unites States accounts for 67 percent of the outflow of water from precipitation (Handson, 1991).

A map was produced (Roy and others, 2005) to estimate how much water is available for recharge to the ground water system or as runoff to streams. The estimate was calculated as the difference between precipitation and potential evapotranspiration summed for all months in the year in which precipitation exceeded potential evapotranspiration. It was indicated that most of the western United States, except for some coastal areas, has far less water available for ground water recharge and use than the rest of the country.

Estimated values of natural ground water recharge are available for the entire United States (Wolock, 2003a) based on base flow separation techniques. Wolock (2003a) produced a 1-kilometer resolution raster dataset as an estimate of mean annual natural ground water recharge. The dataset was created by multiplying a grid of base-flow index values (Wolock, 2003b) by a grid of mean annual runoff values derived from a 1951-80 mean annual runoff contour map (Gebert and others, 1987). The concept used to construct the estimate is based on two assumptions: (1) long-term average natural ground water recharge is equal to long term average natural ground water discharge to streams, and (2) the base flow index reasonably represents, over the long term, the percentage of natural ground water discharge in stream flow.

Natural Recharge to ground water in the entire United States has been estimated as about 1 trillion gallons per day (Nace, 1960).

5.3.4 GROUND WATER STORAGE

Ground water Storage is the amount of ground water available beneath a given area of land surface. The volume of ground water in storage is decreasing in many areas of the United States in response to withdrawals. An estimate indicates that there are about 60000 trillion gallons of ground water in Storage in United States (Nace, 1960).

5.3.5 GROUND WATER DISCHARGE

The percentage of stream flow that is accounted for by base flow for any particular stream is variable across the Nation, Wolock (2003b) estimated the ratio of base flow to total flow, expressed as a percentage (which is called the base flow index) for the conterminous United States.

5.3.6 GROUND WATER QUALITY

National- and watershed-scale information is available on some constituents through State and Federal programs such as the USGS National Water-Quality Assessment (NAWQA) Programme. The NAWQA Program was implemented in 1991 to develop long-term consistent and comparable information on streams, rivers, ground water, and aquatic systems in support of national, regional, State, and local information needs and decisions related to water-quality management and policy. The NAWQA Program is designed to determine the condition of US streams, rivers, and ground water, and the changes in these conditions over time. From 1991 to 2001, the NAWQA Program conducted interdisciplinary assessments and established a baseline understanding of water-quality conditions in 51 of the Nation‟s river basins and aquifers (Hamilton and others, 2004).

5.3.7 WATER USE

The USGS has partnered with State and local agencies to complete estimates of ground-water and surface-water withdrawals for the Nation at 5-year intervals since 1950. The data currently are compiled at the country. State and National levels for eight categorizes of water use – public supply, domestic, irrigation, livestock, aquaculture, self supplied industrial, mining, and thermoelectric power. The most recent compilation is for the year 2000 (Maupin et. al., 2005).

Fresh ground-water withdrawals from 66 principal aquifers in the United States were estimated for irrigation, public-supply, and self-supplied industrial water uses for the year 2000. Total ground-water withdrawals were 76,500 million gallons per day or 85,800 thousand acre-feet per year for these three uses. Irrigation used the largest amount of ground water, 56,900 million gallons per day, followed by public supply with 16,000 million gallons per day, and self-supplied industrial with 3,570 million gallons per day. These three water uses represented 92 percent of the fresh ground-water withdrawals for all uses in the United States, the remaining 8 percent included self-supplied domestic, aquaculture, livestock, mining, and thermoelectric power uses.

Aquifer withdrawals were categorized by five lithologic groups: unconsolidated and semiconsolidated sand and gravel aquifers, carbonate-rock aquifers, igneous and metamorphic-rock aquifers, sandstone aquifers, and sandstone and carbonate-rock aquifers. Withdrawals from aquifers that were not included in one of the 66 principal aquifers were reported in an “Other” aquifers group. The largest withdrawals in the United States were from unconsolidated and semiconsolidated sand and gravel aquifers, which accounted for 80 percent of total withdrawals from all aquifers. Carbonate-rock aquifers provided 8 percent of the withdrawals, and igneous and metamorphic-rock aquifers, 6 percent. Withdrawals from sandstone aquifers, from sandstone and carbonate-rock aquifers, and from the “Other” aquifers category each constituted about 2 percent of the total withdrawals reported.

Fifty-five percent of the total withdrawals for irrigation, public-supply, and self-supplied industrial water uses were provided by the High Plains aquifer, California Central Valley aquifer system, the Mississippi River Valley alluvial aquifer, and the Basin and Range basin-fill aquifers. These aquifers provided most of the withdrawals for irrigation. The High Plains aquifer was the most intensively used aquifer in the United States. This aquifer provided 23 percent of the total withdrawals from all aquifers for irrigation, public-supply, and self-supplied industrial water uses combined, and 30 percent of the total withdrawals from all aquifers for irrigation.

The primary aquifers used for public supply were the glacial sand and gravel aquifers of the North-eastern and North-Central States, the California Coastal Basin aquifers, the Floridan aquifer system, the Basin and Range basin-fill aquifers, and the Coastal lowlands aquifer system along the Gulf Coast. These five aquifers provided 43 percent of the total withdrawals from all aquifers for public supply. The glacial sand and gravel aquifers, Coastal lowlands aquifer system, Floridan aquifer system, and Cambrian-Ordovician aquifer system were the primary sources of water for self-supplied industrial use; these aquifers provided 46 percent of the total ground-water withdrawals for that use.

5.3.8 CONCLUSION

The Regional Aquifer System Analysis carried out in 25 major aquifer systems of the United States have brought out several case studies which have significant contributions in the development of various concepts on groundwater resources estimation. The Regional Scale assessments also highlight the fact that these have important role in precise estimation of National scale assessment. GIS based approach as adopted in US provides a better understanding of ground water resources assessment of an area.

6

Conclusions and Recommendations

6.1 CONCLUSIONS

Ground water resources assessment procedures adopted in different countries for regional level assessments and for country level assessmentswere reviewed(Fig.6.1) with the objective to refine the ground water resource estimation methodology followed in India in the light of best international practices.

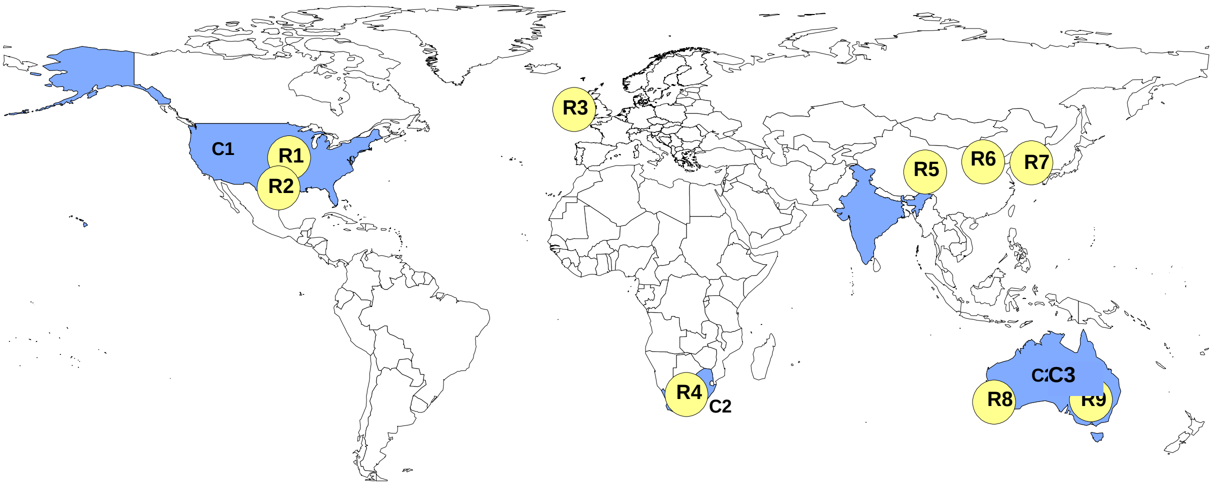


Fig. 6.1: Areas considered for review of international practices of ground water resources assessment.R1 to R9 refer to the areas reviewed for regional ground water resource assessments and C1 to C3 refer to the country level assessments reviewed in this report. **R1**: Kansas, USA; **R2**: Austin, Texas, USA; **R3**:Curragh, Ireland; **R4**:Rietpoort South Africa; **R5**: several locations in China; **R6**: Several locations in Taiwan; **R7**: Soul; **R8**: Perth; **R9**: Murray Darling Basin, Australia. **C1**: United States of America (USA); **C2**:South Africa; **C3**: Australia

The methodologies and procedures followed in different countries have their distinct attributes, but still they have many commonalities. The entire procedure of ground water resources assessment can be split into three distinct processes.

1. Adopting a policy to define exploitable ground water resources
2. Devising a methodology for assessment of ground water resources
3. Operationalisation including data collection, computation and documentation.

6.1.1 EXPLOITABLE GROUND WATER RESOURCES

The exploitable quantity of groundwater resources in an area is defined by the policy adopted by the State. As discussed in detail in the previously in this report, Sustainable Yield Policy implies that exploitable quantity of groundwater resources would be equal to groundwater recharge minus natural groundwater discharge to the stream required to maintain the minimum flow (lean flow) in the stream. Safe Yield policy is to restrict, ground water development to the available replenishable resources.

However, if groundwater is the main source of irrigation in the food belt of the country, then for food security concerns, extraction of groundwater upto sustainable yield limit may not be the feasible option. In such areas, Planned Depletion Policy may be adopted provided the State groundwater regulatory measures are strong enough to control the lowering of groundwater level upto the specified depth. Many countries like those in the Arabian Peninsula do not have any specific policy. Countries like China, Indonesia, Western Turkey, Northern Iraq etc. have adopted safe yield policies. Sustainable yield policy has been adopted in Britain, European Union etc. In Australia and USA different states follow different policies including safe yield, sustainable yield and planned depletion. The existing assessments in India are based on Safe Yield policy. Sustainable yield is generally regarded as thepreferred option since it takes care of ground water dependent ecosystems.

6.1.2 METHODOLOGY FOR GROUND WATER RESOURCES ASSESSMENT

Generally it is recommended to use more than one method for recharge estimation like Water Level Fluctuation, Soil Moisture Balance, Chloride Mass Balance, tracer techniques etc. Numerical Modelling is the preferred method provided data at acceptable level of significance is available. However, while attempting a country-wide estimation, it is preferable to adopt one particular technique as the core method which enables uniformity in assessment and comparison amongst assessment units within the country. Where-ever there is a contradiction between estimation results and field situation, the recharge estimates need to be cross-checked with other techniques. The data elements required for estimation need to be standardized so as to know the significance level of the estimation.

The existing practices of ground water resource estimation in India are comparable to the International Practices. There are many commonalities in the methodology used in India and in countries like South Africa and Australia. The national level groundwater assessment procedure adopted in South Africa is the most detailed information on the subject available in public domain. The gradual refinements in the methodology were brought out in South Africa to address the various groundwater management issues. Major part of the South Africa is covered with hard rock terrains in arid and semi-arid climatic conditions which is similar to Indian conditions. Hence ideas can be drawn from South African approach on assessment of groundwater resources to refine the Indian methodology. The method of determination of the reliability of the estimation is well defined in Australian methodology. Similar system can be introduced in the Indian methodology for qualitative rating of the assessment results. American approach highlights the importance of regional scale aquifer based assessment which form the foundation of national scale assessment in that country. An accurate assessment requires proper understanding of the aquifer disposition, its characterization and groundwater flow system. This is achieved in Regional scale assessment. The parameters of various recharge and discharge components estimated in the Regional scale assessment can be used as norms for assessment in the national scale assessments. Similar practices were carried out in past in India under Water Balance projects.

6.1.3OPERATIONALISATION

The best Indian practices in ground water resource estimation are comparable to international best practices in terms of the scientific principles, techniques and tools used. However, there is a remarkable gap between the international best practices and existing Indian practices in terms of nationwide data collection, R&D studies etc. The best international practices in country wide assessment of ground water resources involves large scale site specific detailed and repetitive scientific studies on ground water resources. So much research has been concentrated on ground water resources in Murray Darling Basin (Australia) that it is referred to as a ‘laboratory’ for ground water resource assessment. Australia and USA has completed regional ground water modelling studies. Many countries in European Union, Australia, USA, Korea, Taiwan and others have adopted registration of wells and metering of ground water draft. Though illegal constructions and incomplete metered data is common in these cases, there are representative samples for extrapolation. Site specific field studies on ground water recharge estimation and metering of ground water draft are the two fields where Indian practices require much improvement.

The documentation procedures followed in different countries is comparable to Indian practices in terms of contents. The best international practices use web based interactive maps to communicate the ground water resources data to the public.

6.2 RECOMMENDATIONS: A NEW APPROACH FOR ESTIMATION OF GROUND WATER RESOURCES IN INDIA

A new methodology is evolved considering the limitations in the existing methodology and considering the international best practices. The proposed methodology is a trade-off between best scientific techniques and its applicability on a country scale. Salient features of the proposed methodology are discussed below.

6.2.1 EXPLOITABLE GROUND WATER RESOURCES

Groundwater resources assessment to be carried out based on Sustainable Yield Policy which implies that exploitable quantity of groundwater resources would be equal to groundwater recharge minus natural groundwater discharge to the stream required to maintain the minimum flow (lean flow) in the stream.

6.2.2 GEOGRAPHICAL BASE FOR ASSESSMENT

The geographic unit of assessment of groundwater resources of the country would be aquifer. Therefore the basic pre-requisite of assessment in a region is establishment of physical disposition of the aquifer systems, characterization of individual aquifers and groundwater flow system occurring within the aquifer system. The first level of establishment of Principle Aquifer Systems of the country would be at the scale of 1:250,000. Second level of aquifer mapping would be Regional Aquifer Systems at the scale of 1:50,000. Third level of aquifer mapping would establish Micro Aquifer Systems at the scale of 1:10,000.

The basic unit of assessment would be aquifers at 1:10,000 scale. Till the time, aquifer map at 1:10,000 is not available in the state, the assessment unit would be a hydrologic unit having defined hydrogeological boundaries like – micro watershed in hard rock terrain, doab in alluvial terrain and catchment area in hilly terrain. Further, wherever (micro) aquifers have larger geographical area covering more than one hydrologic unit, the lower geographical entity (hydrologic unit) would be the assessment unit. Final assessment may be apportioned and presented in aquifer basis.

Since the ground water resources assessment is to be presented on aquifer basis, the methodology for assessment is defined separately for phreatic and confined aquifer. Section 6.2.3 to 6.2.12 enumerates the methodology for assessment in phreatic aquifer and Section 6.2.13 touched upon the assessment of ground water resources in confined aquifer.

6.2.3WATER BALANCE EQUATION

The following equation is a generalised form of water balance equation, which applies to any assessment unit irrespective of it being an administrative unit,a watershed or an aquifer. This water balance equation (eq. 6.1) holds good for any part of the year and for the annual water balance as well.

$$\Delta S = R^{rainfall} + R^{other} - B - GE^{all} - ET \pm L \pm O^{inflow\ /outflow} \text{ ....6.1}$$

Where

ΔS =Change in storage in ground water reservoir

$R^{rainfall}$ =Recharge from rainfall

R^{other} =Recharge from other sources

B = Baseflow

GE^{all} = Ground water draft for all uses

ET = Evapotranspiration losses

L =Leakage to or from deeper aquifers

$O^{inflow\ /outflow}$ =Net inflow/outflow across the boundary of the assessment unit

The above equation can be rewritten as

$\Delta S = R^{rainfall} + R^{other} - GE^{all} \pm V_{out}^{net}$ 6.2

Where the new term introduced V_{out}^{net} is the net inflow/ outflow from the unit which is the resultant of baseflow, evapotranspiration losses, leakage from or to the deeper aquifers, net flow across the boundaries etc.

One of the major limitations of the existing methodology (GEC'97) is that in an attempt to simplify the water balance equation it completely ignores the net inflow/outflow term. A complete assessment of ground water resources should include assessment of all the components of the above water balance equation (eq. 6.1). However, if the unit chosen is a watershed in a hardrock area with a single aquifer system, the components like Land$O^{inflow\ /outflow}$ of eq.6.1 can be neglected. However, there cannot be a generalised assumption. It is left to the judgement of the professional doing the assessment to include or neglect any component based on field conditions and to formulate the water balance equation accordingly.

6.2.4 ESTIMATING COMPONENTS OF THE WATER BALANCE EQUATION

i. Change in storage (ΔS)

Change in storage can be estimated from water level fluctuation, area and representative specific yield (eq.6.3)

$\Delta S = \Delta h \times Area \times S_y$.........................6.3

Where

Δh = water level fluctuationin the period of assessment (between May and November)

$Area$ = area of the assessment unit

S_y= Representative specific yield value.

ii. Recharge from rainfall ($R^{rainfall}$)

There could be two approaches to estimate Recharge from Rainfall

a. **As a residual using equation 6.1**

If sufficient data is available for independent assessment of all the components (except recharge from rainfall) of the water balance equation (eq. 6.1), then recharge from rainfall should be estimated as a residual (eq. 6.4).

$R^{rainfall} = \Delta S - R^{other} + B + GE^{all} + ET \pm L \pm O^{inflow\ /outflow}$ 6.4

For description of terms please see eq. 6.1

If recharge from rainfall is obtained from eq. 6.4, then it has to be normalised as per the existing practice. If rainfall and corresponding recharge figures for more than three years is available then the normalisation should be based on a linear regression between rainfall and recharge (eq. 6.5). If recharge estimate is available only for one period, the normalisation can be achieved using the relation given in eq. 6.6.

$R_{Normal}^{rainfall} = a \times R^{rainfall} + b$...........................6.5

Where a and b are the regression coefficient and y-intercept respectively, which are obtained from regression analysis of rainfall and recharge.

$R_{Normal}^{rainfall} = R^{rainfall} \times \frac{NormalRainfall}{Rainfallint\ heyearofass\ essment}$.......................6.6

b. Independent assessment

Recharge from rainfall can also be assessed using many independent methods as described in Chapter2. These figures could be used directly or relation between rainfall and recharge can be worked out to find out representative rainfall infiltration factors for assessment of recharge from rainfall (eq. 6.7)

$R^{rainfall} = Normal\ Rainfall \times Rainfall\ Infiltration\ Factor\ (RIF)$ 6.7

As a broad guideline, it is proposed to estimate $R^{rainfall}$ as a residual from eq. 6.4 if all the estimated (known) components of the equation has Significance Index of atleast '2' (see section 6.2.9).

iii. Recharge from other sources (R^{other})

Recharge from other sources is estimated by adding recharge from all sources other than rainfall (eq. 6.8)

$R^{other} = R^{canal} + R^{irr\_sw} + Is + R^{irr\_gw} + R^{Tanks} + R^{WC}$.......................6.8

Where
R^{canal} = Recharge due to canal seepage
R^{irr_sw}= Recharge due to return flow from surface water irrigation
R^{irr_gw}= Recharge due to return flow from ground water irrigation
R^{Tanks} = Recharge from tanks and ponds
R^{WC}= Recharge from water conservation structures.
Is =Recharge from streams to ground water

In absence of site specific measurements the norms recommended in GEC'97 can be used to estimate the above components.

iv. Ground water extraction (GE)

Groundwater extraction or draft is to be assessed use-wise.

$GE^{all} = GE^{domestic} + GE^{irrigation} + GE^{industrial}$ 6.9

Where,
GE^{all} =Ground water Extraction for all uses
$GE^{domestic}$ =Ground water Extraction for domestic uses
$GE^{irrigation}$ =Ground water extraction for irrigation
$GE^{industrial}$ = Ground water extraction for industrial uses

Ground water extraction can be estimated using the standard methods as outlined in Chapter 2 of this report and the GEC'97.

v. Net outflow/inflow (V^{net}_{out})

Net outflow/inflow ($\boldsymbol{V^{net}_{out}}$) is the resultant of inflow/outflow terms as described in eq. 6.1 and 6.2. There are two approaches to estimate the $\boldsymbol{V^{net}_{out}}$term.

a. Independent assessment

If sufficient data is available, all the components can be assessed independently. Baseflow can be calculated based on stream gauge monitoring station. ET can be estimated based on Potential

Evapotranspiration measurements, independent water balance studies, lysimeter studies, even remote sensing studies also. Leakage to / from deeper aquifer is based on transmissivities and differences in hydraulic heads between the aquifers. Inflow and outflow across the boundary can be calculated through application of Darcy law and numerical ground water flow modelling. If independent assessment of the above terms is available, recharge from rainfall can be estimated as a residual from equation 6.2.

b. As a residual using eq. 6.2

In cases, where independent measurement of each term is not possible due to paucity of data, V_{out}^{net} can be considered as a single term which represents the resultant of Baseflow, Evapotranspiration losses, Leakage to or from deeper aquifers and Net inflow/outflow across the boundary of the assessment unit.V_{out}^{net} as a single term can be estimated as a residual using eq.6.2 if independent assessments of all other components in eq.6.2 including recharge from rainfall is available. It is to be noted that the terms $R^{rainfall}$ and V_{out}^{net} cannot be estimated as residuals simultaneously. One can be estimated as a residual only when independent assessment for the other is available.

6.2.5 SEASONAL COMPUTATION OF RECHARGE/DISCHARGE COMPONENTS

To represent the spatial variations in the ground water dynamics, it is recommended that the recharge/discharge components should be estimated for at least two different periods. Period 1: 1st June to 1st November- in most of the states this period coincides with the monsoon period or the khariff period. And the period 2 is 1st November to 30th May (non-monsoon or rabi period). Recharge from rainfall during the non-monsoon period is to be estimated only when the normal non-monsoon rainfall accounts for more than 10% of the normal annual rainfall as recommended in GEC'97. Table 6.1 provides a summary of the componentsof the water balance components, which are to be estimated

Table 6.1: Components of water balance equation, which are to be assessed.

Component of water balance	Description
ΔS	Change in storage considering water level fluctuation between May and November
$R_{Normal}^{rainfall}$	Recharge from rainfall during monsoon as well as non monsoon period
R^{other}	Recharge from other sources during monsoon as well as non-monsoon period.
GE^{all}	Ground water extraction for different purposes during monsoon as well as non-monsoon period.
V_{out}^{net}	Net outflow/inflow to be estimated for both monsoon and non monsoon period

6.2.6 GROUND WATER RESOURCE AVAILABILITY

i. Annual replenishable recharge

It is to be estimated by adding the recharges from rainfall and recharges from other sources both during monsoon as well as non monsoonperio

$$R_{annual}^{all} = R_{monsoon}^{rainfall} + R_{non-monsoon}^{rainfall} + R_{monsoon}^{other} + R_{non-monsoon}^{other} \quad \text{..........................6.10}$$

Where the R stands for recharge, the superscript denotes source of recharge and the subscript specifies the period.

ii.Annual Exploitable Ground water Resource(EGR_{annual})

It is the amount of recharge available for use after discounting the minimum flow requirements in the rivers (B_{min})

$EGR_{annual} = R_{annual}^{all} - B_{min}$ 6.11

6.2.7STAGE OF EXPLOITATION (SOE)

Stage of ground water exploitation is to be estimated considering annual extraction and annual exploitable ground water resources as follows

$SOE = \frac{GE^{all}}{EGR_{annual}}$...6.12

Since as per the policy, groundwater extraction should be restricted to Exploitable Ground Water Resources, in case annual groundwater extraction is more than exploitable ground water resources, it will be termed as 'Over-exploitation'. There are however, two exceptional conditions when evenif the SOE is >100%, 'over-exploitation' would not be considered –

a. *When depth to groundwater level is within 5 m below ground level.* This is because groundwater level can be lowered upto 5m to avoid waterlogging condition.
b. *If the long term post-monsoon water level trend do not indicate significant decline in water level.* This situation implies that the unsaturated zone created within the aquifer because of groundwater extraction is recharged during subsequent rainfall. Thus natural recharge is actually enhanced due to extraction of groundwater.

6.2.8 VALIDATION OF SOE

SOE values are to be validated with water level data. The mismatch conditions are enumerated below(table 6.2):

Table 6.2: Broad guidelines for validation of estimated Stage of Exploitation (SOE)

SOE	Non-Acceptable Conditions
Upto 100%	Significant decline in both pre-monsoon and post-monsoon long term water level trend
> 100%	No significant decline in both pre-monsoon and post-monsoon long term water level trend Significant contribution to stream flow from ground water. (When SOE is greater than 100%, the lean period flows in the streams are expected to be negligible)

In case of mismatch between estimation results and water level data, following procedure to be adopted –

i. All the key data elements to be checked. In case any data element is in the lowest rank of accuracy, it should be brought to atleast the next higher level of accuracy.
ii. In case, field situation indicates that one or more inflow / outflow components like lateral inflow, lateral outflow, leakage to deeper aquifer etc. which is not computed in the assessment but is dominant in the prevailing water balance of the area, the same should be estimated and brought in the water balance equation mentioned at equation 6.1.
iii. If the mismatch persists after Step '1' (and Step '2' if applicable), Alternate techniques to be adopted for assessment of 'Rainfall Recharge', 'Recharge from Other sources' and 'Ground Water Draft estimation'

6.2.9 RATING OF ASSESSMENT–SIGNIFICANCE INDEX

The quality of assessment to be rated based on significance level of the data elements used. An arithmetic tool can be employed for determining the 'Significance Index' of the assessment. The significance levels for each data elements can be categorized as 'Low', 'Medium' and 'High'. Other than these three categories, there can be situations of 'No data' and 'Not Applicable'. Seventeen (17) numbers of data elements have been listed in Table 6.3.Broad guidlines for assigning significance levels to individual data elements are given in Table 6.4. The major data elements have sub-datasets. The significance index can be computed as follows.

Table 6.3 : Data elementsrequired for ground water resource assessment

Measured data	***Parameters***
1. Rainfall	11. Rainfall Recharge factor
2. Water level	12. Specific Yield
3. Canal data – canal length, bed width, full supply, side angle, lining, number of running days, no. of outlets, design discharge of outlets	13. Recharge factor – water conservation structures
4. Cropping Pattern – area	14. Return flow factor – Surface water irrigation
5. Abstraction structures - numbers	15. Return flow factor – Ground water irrigation
6. Tanks and Ponds – number, water spread area, number of days water is available	16. Seepage factor – tanks
7. Water Conservation Structures – storage capacity, number of fillings, volume recharged	17. Canal Seepage factor
8. Population	18. Unit Ground Water Draft
9. Spatial Data of assessment units – area, vertical disposition	
10. Stream flow	

Example 6.1: *Calculation of Significance Index*

Significance Index of water resource assessment of abc Assessment Unit

Significance Level	**No. of items in this category**
Low (1)	7
Medium (2)	4
High (3)	3
Not Applicable (3)	4
Total	18
Significance index*	59%

$$\text{* Significance index of the Assessment of abc Unit} = \frac{1\times 7+2\times 4+3\times 3}{18-4} = 2(Medium)$$

Table 6.4: Guidelines for assigning significance levels to individual data elements

a. RRF, Sp. Yld.	
Data source	**Significance Level**
Determined for Principle Aquifer System	Low (1)
Determined for Regional Aquifer System	Medium (2)
Determined for Micro Aquifer System	High (3)
b. Unit Draft	
Determined for Principle Agro-climatic zones (Planning Commission classification – 15 nos.)	Low (1)
Determined for sub Agro-climatic zones (National Agricultural Research Project – 127 nos.), no. of survey >10, statistically analyzed	Medium (2)
Determined for Assessment Unit, no. of survey >10, statistically analysed	High (3)
c. Water level	
1 well > 100 sq. Km. , < 5 yrs. Water level data, not validated	Low (1)
1 well ≥ 50 sq. And ≤ 100 sq. Km., > 5 yrs. Water level data, Validated as per established protocol	Medium (2)
1 well ≤ 50 sq. , ≥ 10 yrs. Water level data, Validated as per established protocol	High (3)
d. Abstraction Structure	
Well census, no field checks	Low (1)
Well census, limited field checks (<1%) for error computation	Medium (2)
Well census, field checks (>1%) for error computation	High (3)
e. Others	
No documentation on specific studies is available	Low (1)
Documentations on specific studies are available	Medium (2)
Site specific field values are available	High (3)

6.2.10 LINKAGE BETWEEN ASSESSMENT AND MANAGEMENT

In order to prioritise areas for implementation of various ground water management programmes like artificial recharge, rainwater harvesting, ground water regulation etc. A categorisation scheme is introduced. This scheme incorporates the following aspects

i. Ground water recharge
ii. Ground water extraction
iii. Temporal availability of ground water recharge
iv. Ground water accessibility
v. Ground water quality

The Category Index is defined as

$$\boldsymbol{CI = SOE \times T_{avail} \times EF \times QF} \text{...} 6.13$$

Where
CI=Category Index
SOE=Stage of Exploitation
T_{avail} = Temporal availability
EF = ExtractabilityFactor
QF =Quality Factor

This categorisation index is proposed to be estimated on a GIS environment using index overlay method and the final results are to be depicted on a map. Following indices are recommended to be considered for map based calculation of Categorisation Index (CI)

a. Stage of Exploitation (*SOE*)

The physical quantification of Ground Water Recharge and Extraction is manifested in *Stage of Groundwater Exploitation*. The SOE indices may be taken as follows

Table 6.5: Recommended SOE Indices

Stage of Exploitation (%)	SOE Index
0-50	75
50-70	40
70-100	15
Over exploited	0

b. Groundwater Accessibility and Extractability Factor (*EF*)

The concept of *Groundwater Accessibility* is based on the fact that the Ground Water recharge estimates do not give an indication of what can practically be pumped out of an aquifer unit. The extraction of ground water resources depends on the rate at which groundwater is transmitted within the aquifer material i.e. the hydraulic conductivity or transmissivity of the aquifer systems. However, good information on distributions of hydraulic parameters is as often as not, unavailable. Since there is a good correlation between well yield and transmissivity, the degree of Ground Water Accessibility is reflected in borehole yield distributions. Therefore 'well yield' can be used as an index of Ground Water Accessibility, which is termed as *Extractability Factor* (EF).

Table 6.6: Recommended EF Indices

Yield (Drill time discharge)	EF
< 2 lps	0.10
2 to 5 lps	0.30
5 to 10 lps	0.60
10 to 25 lps	0.80
> 25 lps	1.00

c. Ground Water Quality (QF)

The *Ground Water Quality* is an important consideration in ground water management issues. Therefore alongwithquantity, there should be a rating of the quality also based on degree and extent of contamination. A rating of groundwater quality is given in the following table which can be numerically converted into *Quality Factor* (QF).

Table 6.7: Recommended indices for ground water quality

Prevailing water quality situation	Quality Factor (QF)
Unmodified, pristine conditions- Natural groundwater quality conditions prevail	1.00
Localised, low levels of contamination, but no negative impacts apparent- Largely natural groundwater quality conditions prevail	0.90
Moderate levels of localised contamination, but little or no negative impacts apparent- Some localised contamination detected; may impact the purpose for which groundwater is used	0.70
Moderate levels of widespread contamination, which limit the use or potential use of the aquifer- Groundwater contamination is quite widespread but levels are relatively low; may impact the purpose for which groundwater is used	0.50
High levels of local contamination, which render parts of the aquifer unusable- High levels of contamination detected in places; use of groundwater from impacted area to be restricted or prohibited	0.10
High levels of widespread contamination which render the aquifer unusable- Very high levels of contamination widespread throughout the aquifer. Groundwater use to	0

be restricted or prohibited.

d. Temporal Availability of Ground water resources (T_{avail})

Temporal variation in availability of Ground water resources (recharge) particularly in hard rock terrain is not uniform throughout the ground water year. The monsoon recharge in hard rock terrain often dissipates at a faster rate resulting in lesser availability of the resource on field during lean (non-monsoon) period than projected in monsoon recharge estimation. Therefore a factor called Temporal Availability Factor (T_{avail}) is introduced as follows (Table 6.8):

Table 6.8: Recommended indices for Temporal availability

$EGR_{leanperiod}$	T_{avail}
$\Delta S_{\text{lean period}} \geq 50\%$ of ΔS_{Rabi}	1.0
$\Delta S_{\text{lean period}} \geq 33\%$ &< 50% of ΔS_{Rabi}	0.75
$\Delta S_{\text{lean period}} < 33\%$ of ΔS_{Rabi}	0.50

$\Delta S_{leanperiod}$ andΔS_{Rabi} can be estimated using eqations 6.14 and 6.15 as follows

$$\Delta S_{Rabi} = \Delta h_{May-Nov} \times Area \times S_y \text{.........................} 6.14$$

$$\Delta S_{leanperiod} = \Delta h_{May\,(prev.yr.)-Jan} \times Area \times S_y \text{.........................} 6.15$$

Where

ΔS_{Rabi} = Available ground water resources during rabi period

$\Delta S_{leanperiod}$ = available ground water resources durig lean period

$\Delta h_{May-Nov}$ = Fluctuation in water table from May to November in the year of assessment

$\Delta h_{May\,(prev.yr.)-Jan}$ =Fluctuation in water table from May (previous calendar year) to January

$Area$ = Area of the assessment unit

S_y = Specific yield.

Example 6.2: *GIS based calculation of category indices*

GIS based procedure recommended for calculation of the category indices is demonstrated here with a case study considering a sample area from Seonath sub-basin covering three blocks (Durg, Patan and Gunderdehi) of Durg district in Chhattisgarh State. The calculation is done in two broad steps. i. Preparation of input maps ii. Calculation of category indices using these input maps

Input maps

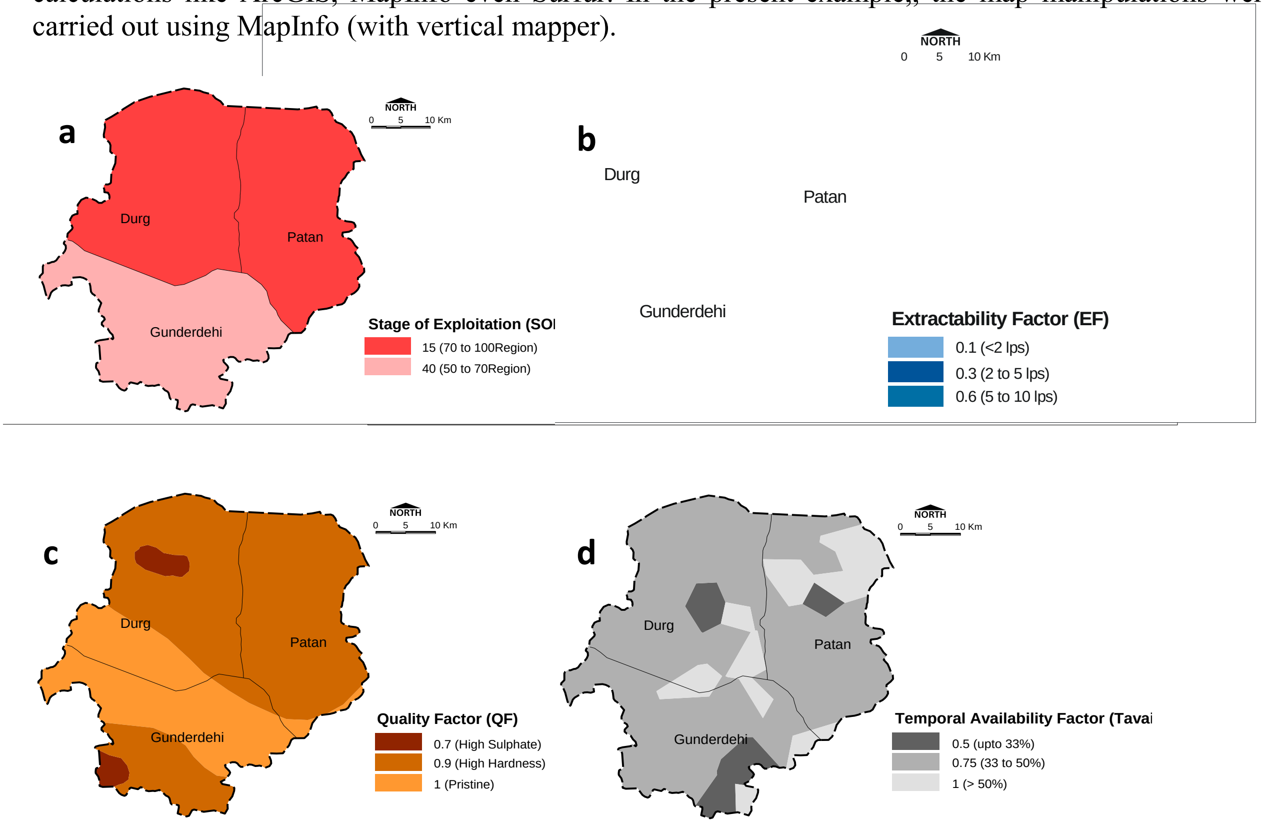
The procedure requires four input maps (6.2 a to d). Existing estimates of block wise stages of ground water development were considered for assigning SOE indices (Fig.6.2a, Table 6.5). Drill time discharges (Yield) of exploratory wells were translated into Extractability Factor (Fig.6.2b, Table 6.6). Reported ground water quality issues were considered for assigning Quality Factor (The sulphate affected areas are exaggerated for better demonstration of the estimation procedure) (Fig. 6.2c, Table 6.7).

Temporal availability Factors were estimated from DTW data. Thiessen polygons were constructed for each observation well. Rabi and lean period ground water availabilities (eq. 6.13 and 6.14) and their ratio were estimated for each polygon. Based on the ratios, the temporal availability factor (T*avail*) were assigned (Fig. 6.2d, table 6.8)

Calculation of Category Indices

The four input maps thus prepared are then rasterised. The product of these four input raster maps is the resultant raster map with the category indices. The resultant category indices were then contoured

(Fig. 6.2e). These map manipulations can be done using any software that supports map based calculations like ArcGIS, MapInfo even Surfur. In the present example,, the map manipulations were carried out using MapInfo (with vertical mapper).



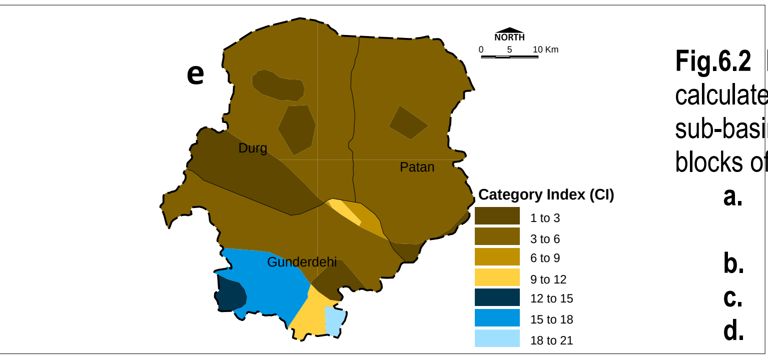


Fig.6.2 Input maps and resultant category indices calculated for a case study area in parts of seonath sub-basin comprising Durg, Patan and Gunderdehi blocks of Durg district, Chhattisgarh.

a. Stages of Exploitation (SOE) and SOE indices
b. Extractability Factors (EF)
c. Temporal Availability Factor (Tavail)
d. Quality Factor (QF)
e. Category Indices (CI)

6.2.11 CATEGORY AND GROUND WATER MANAGEMENT PROGRAMME

Following guidelines are recommended as ground water management option in the areas with specific category indices. While devising detailed management plans all the attributes like recharge, exploitable resources, ground water resource availability in rabi and lean periods, ground water draft for different purposes, stage of exploitation, extractability of ground water, quality of ground water etc. are to be considered.

Table 6.5: Category and water management programme

Category Index (CI)	Management Option
Between 12 and 75	Areas suitable for ground water development. More the CI, higher is the feasibility for ground water development.
Greater than 0 but less than 12	Areas for implementation of artificial recharge and rainwater harvesting. Lower the CI, higher is the priority of the area for management interventions

CI=0	Areas to be considered for regulation

6.2.12 TOTAL AVAILABILITY OF GROUND WATER RESOURCES

i. In-Storage Resources ($R_{in-storage}^{phreatic}$)Assessment

$R_{in-storage}^{phreatic} \quad = T_h \times S_y \times Area$...............................6.15

Where

T_h is the thickness of the aquifer (granular/productive zone) below the zone of water level fluctuation. andS_y is the representative specific yield

ii. Total Availability

Total availability (R_{Total}) is the sum total of Dynamic (R_{annual}^{all}) and In-storage ($R_{in-storage}^{phreatic}$) resources.

$$R_{Total} \;=\; R_{annual}^{all} + R_{in-storage}^{phreatic}$$

The assessment of Total Availability of ground water resources in the aquifer is important, since it gives an idea of the ***'Usable lifetime of the aquifer'*** particularly for the over-exploited aquifers. Usable lifetime of the aquifer can be defined as the estimated number of years remaining during which a region of the aquifer can sustain past levels of decline without significant impairment of existing uses. The estimates of Usable Lifetime of the aquifer are not *predictions* of aquifer depletion, but rather *projections* – what would probably happen if past rates and patterns of use continue into the future. Usable lifetime is defined here as the number of years remaining until water-level declines reach a 'pre-defined water level' at which large-volume irrigation, municipal, or industrial pumping is likely to be impractical.

6.2.13 GROUND WATER RESOURCES ASSESSMENT IN CONFINED AQUIFER

Areas characterized by multi-layered aquifer system need to have separate assessment for each aquifer. Moreover, where ground water extractions from the deeper (below the phreatic aquifer) aquifers are prevalent, an assessment of the availability and withdrawal from the deeper aquifer is necessary for holistic ground water management strategy. Assessment of ground water resources in the aquifers below confining layer need to be carried out taking into consideration the following points –

- In case, the upper phreatic aquifer is hydraulically connected with the lower aquifer, the methodology described in the previous sections to be followed.
- Precise assessment of ground water resources in confined aquifer need to be carried out by ground water modelling approach.
- A preliminary assessment of the availability and draft from the confined aquifer may be undertaken using a simplified methodology involving lesser data inputs.
- Theoretically, availability of ground water resources in confined aquifer have two components: Storage under pressure (using Storativity concept) and Storage under desaturated (gravity drainage) condition (using Specific Yield concept). However, since ground water withdrawals from confined aquifer are known to have serious environmental degradation effects, the preliminary assessment of ground water resources in confined aquifer is restricted to the estimation of ground water storage under pressure conditions only.
- Precise assessment of ground water draft from confined aquifer is difficult since the wells tapping the confined aquifer generally also taps the potential zones in the upper phreatic aquifer. Therefore the yield of the wells is the combined yield of all the potential zones upto the total depth of the well. Hence, logical approximations of the ground water draft from confined aquifer

have to be arrived at in order to assess the ground water utilization scenario in these aquifers. Assuming that the extractions from each aquifer is proportional to the respective Transmissivities, a quick approximation can be made using the available transmissivity values.

- Preliminary assessment of the ground water resources in confined aquifer does not imply that the assessed resource is available for exploitation. The objective of this exercise is to have an overview of the ground water regime in the particular confined aquifer. It should be kept in mind that any significant ground water withdrawal from confined aquifer may invoke serious environmental degradation problem. Therefore, in case the preliminary assessment reveals that ground water is being withdrawn in significant quantity for any confined aquifer, that particular aquifer should be identified for detailed assessment using numerical modelling approach.

a. *Ground Water Resource in Confined Aquifer*

$$R_{in-storage}^{confined} = (h_{min} - h_0) \times S_s \times A \text{......................................6.16}$$

Where

$R_{in-storage}^{confined}$ = Ground water resource in confined aquifer
S_s=Specific Storage
h_{min} = Lowest piezometric head (amsl)
h_0 = Bottom of the confining layer (amsl)
A = Area

b. *Ground Water Draft from Confined Aquifer*

Annual Ground Water Draft = Annual unit draft X number of wells

The unit draft to be calculated as follows –

- If the yield of wells tapping individual aquifer is known through ground water exploration, then average yield ratio of the individual aquifers is to be multiplied with the actual (cumulative) rate of extraction from the well obtained in sample survey.
- Alternatively, ratio of yield for individual aquifers is to be determined based on the average length of the zones tapped in individual aquifer and qualitative grading of the potentiality of the aquifer material.

c. *GIS based classification in confined aquifer*

Information on confined aquifer can further be classified on GIS platform in case information on spatial variation of storativity, draft and ground water quality is available. In such cases, Storativity layer, draft layer and Quality layer can be superimposed in a manner similar to that depicted in fig 6.2 to obtain the variability in the ground water situation in the confined aquifer.

6.3 OPERATIONALISATION

In light of the international best practices, the following three major interventions are recommended to improve the process of ground water resource estimation in India (Fig.6.3).

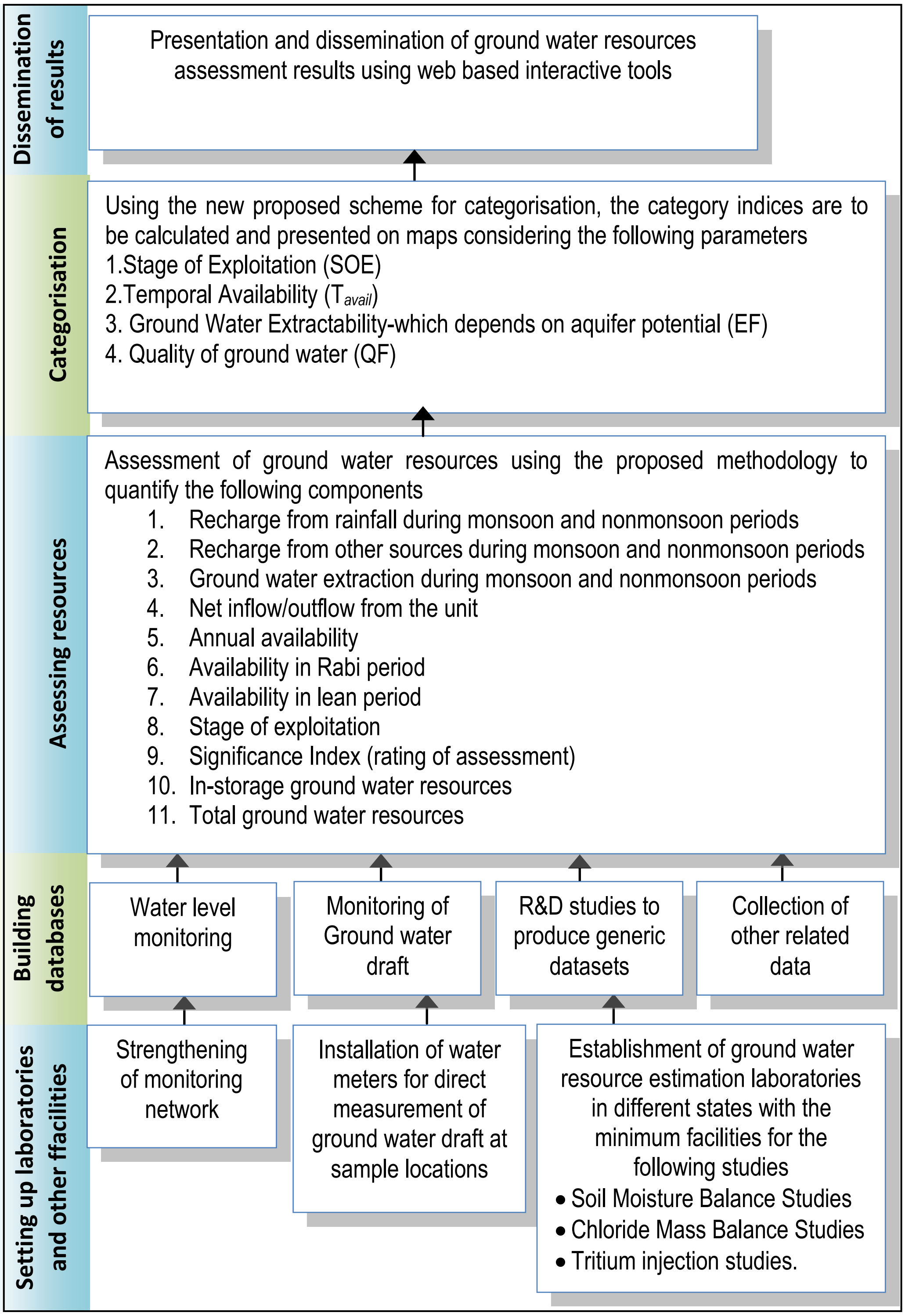
i. The strength of best country wide resource assessment is intensive field investigations involving advanced tools and techniques. It is recommended to promote R&D studies on ground water resource estimation in different parts of the country. To boost R&D studies, it is recommended to set up ground water recharge assessment laboratories in all the States. The laboratories should be equipped to carry out experiments related to at least three studies-i. Soil Moisture Studies ii. Chloride Mass Balance and iii. Tritium injection studies. These studies would be aimed at producing factors, parameters, empirical relations and over all understanding of ground water dynamics. These in turn will provide generic datasets, which can be used for rapid and realistic country wide assessment

ii. In the entire process of ground water resource assessment and ground water management, estimation of ground water draft is the most important component. Ironically it is the weakest link in ground water resource assessment in India and elsewhere. As discussed above, in many countries like Australia, USA, Korea, Taiwan etc abstraction structures are registered and ground water draft is metered. We recommend to initiate direct metering of ground water draft in select irrigation and domestic wells and in all wells established for industrial purpose. Enforcing fitting of water meters and recording draft in all govt. funded wells could be a feasible option. The unit drafts obtained from these sample surveys can be used to assess ground water draft.

iii. It is recommended to create a GIS based village wise database of all primary information and data related to estimation of ground water resources. It is also recommended to carry out the estimations on a GIS platform. The final output is recommended to be depicted on maps and should be accessible using web based interactive tools.

6.4 POSTSCRIPT

The methodology described above has been developed around the core principle of the existing methodology of ground water estimation in India viz. GEC. During successive assessments in the country, managers, planners and stakeholders in ground water sector raised concerns on certain issues on ground water assessment. The proposed refinements in the methodology have been carried out addressing those points with the help of lessons learned from study of international assessment practices. The methodology is a guideline to facilitate country-wide assessment in a systematic and scientific manner.The bottomline of success of the assessment methodology remains on the quality of data used for the study and the logical application of the methodology keeping in mind the prevailing hydrogeological setup of the assessment area.



Presentation and dissemination of ground water resources assessment results using web based interactive tools

Using the new proposed scheme for categorisation, the category indices are to be calculated and presented on maps considering the following parameters
1.Stage of Exploitation (SOE)
2.Temporal Availability (T_{avail})
3. Ground Water Extractability-which depends on aquifer potential (EF)
4. Quality of ground water (QF)

Assessment of ground water resources using the proposed methodology to quantify the following components

1. Recharge from rainfall during monsoon and nonmonsoon periods
2. Recharge from other sources during monsoon and nonmonsoon periods
3. Ground water extraction during monsoon and nonmonsoon periods
4. Net inflow/outflow from the unit
5. Annual availability
6. Availability in Rabi period
7. Availability in lean period
8. Stage of exploitation
9. Significance Index (rating of assessment)
10. In-storage ground water resources
11. Total ground water resources

Water level monitoring

Monitoring of Ground water draft

R&D studies to produce generic datasets

Collection of other related data

Strengthening of monitoring network

Installation of water meters for direct measurement of ground water draft at sample locations

Establishment of ground water resource estimation laboratories in different states with the minimum facilities for the following studies
- Soil Moisture Balance Studies
- Chloride Mass Balance Studies
- Tritium injection studies.

Fig. 6.3: Summary of the proposed ground water resources assessment procedure in India.

References

Alley WM, Leake SA (2004) The journey from safe yield to sustainability. *Groundwater*. 42(1): Jan–Feb

American Society of Civil Engineering (1961) Ground-water basin management. Manual of Engineering Practice no. 40, p 52.

American Society of Civil Engineering (1972) Groundwater management.Manual of Engineering Practice 40.

Allison GB, 1988. A review of some of the physical, chemical and isotopic techniques available for estimating ground water recharge, in Simmers, I., ed., Estimation of natural recharge of ground water: North Atlantic Treaty Organisation, Advanced Science Institutes Series, v. 222, p.49-72.

Allison GB, Hughes MW (1978) The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer. Aust J Soil Res 16:181–195

Anderson M P (2005) Heat as a Ground Water Tracer, GROUND WATER, Vol. 43, No. 6 pp. 951–968

Arnold JG, Allen PM, Muttiah R, Bernhardt G (1995) Automated base flow separation and recession analysis techniques. Ground Water 33:1010–1018

Arnold JG, Williams JR, Nicks AD, Sammons NB (1989) SWRRB – a watershed scale model for soil and water resources management. In: Singh VP (ed) Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, Colorado, pp 847–908

Australian Water Resource Assessment 2000 - surface and groundwater availabilityand quality, a report of the National Land and Water Resources Audit (Audit).

AWR (2005) Australian Water Resources 2005-A baseline assessment of water resources for the National Water Initiative Key Findings of the Level 2 Assessment Summary Results Australian Government National Water Commission 97p.

Allen, RG, Pereira LS, Raes, D, Smith M. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage Paper 56. FAO, Rome.

Bredehoeft JD, Papadopulos SS, Cooper HH Jr (1982) The water budget myth. In: Scientific basis of water resource management studies in geophysics. National Academy Press, Washington,DC, pp 51–57.

Bredehoeft JD (1997) Safe yield and the water budget myth. *Ground Water* 35(6):929.

Bredehoeft JD (2002) The water budget myth revisited: why hydrogeologists model. Ground Water 40(4):340–345.

Bredehoeft JD (2004) Reply to M. Sophocleous in discussion of papers section (C. Neuzil discussion editor).*Groundwater* 42(4) 618–619, July–August.

Bouwer H (1978) Groundwater hydrology. McGraw-Hill, New York.

Begemann F and Libby WF (1957) GeochemCosmochimActa12 277

Belan RA, Matlock WG (1973) Groundwater recharge from a portion of the Santa Catalina Mountains. In: Proc Meeting Hydrology and Water Resources in Arizona and the Southwest, Arizona Section, American Water Resources Association, and the Hydrology Section, Arizona Academy of Science, Tucson, Arizona, Rep 3, pp 33–40

Birkle P, Rodríguez VT, Partida EG, 1998. The water balance for the Basin of the Valley of Mexico and implications for future water consumption Hydrogeology Journal 6:500–517

Bredehoeft, J.D., and I.S. Papadopulos. 1965. Rates of vertical ground-water movement estimated from the Earth’s thermal profile. Water Resources Research 1, no. 2: 325–328.

Bredehoeft, J.D., and I.S. Papadopulos. 1965. Rates of vertical ground-water movement estimated from the Earth's thermal profile. Water Resources Research 1, no. 2: 325–328.

Bredenkamp, D.B., Botha, L.J., van Tonder, G.J. and van Rensburg, H.J., 1995. Manual on Quantitative Estimation of Groundwater Recharge and Aquifer Storativity. WRC Report TT 73/95, Pretoria, South Africa, pp. 407.

Barnett BG and Muller J (2008) Upper Condamine Groundwater Model Calibration Report. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. 51pp.

Barnett BG and Muller J (2008) Upper Lachlan Groundwater Model Calibration Report. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. 58pp.

Bell M (2001) What threat is salt to my farming operation? *Australian Grain* October-November, Northern Focus, i-iii.

Biggs AJW, Power RE (2003) A review of salinity occurrences in the Queensland Murray-Darling Basin. Department of Natural Resources and Mines, Brisbane, Queensland, QNRM03018.

Baron J, Seward P and Seymour A (1998) The groundwater harvest potential map of the Republic Of South Africa. Technical Report: Gh 3917, DWAF.

Bredenkamp DB, Botha LJ, van Tonder GJ, and Janse van Rensburg H (1995) Manual on quantitative estimation of groundwater recharge and aquifer storativity. WRC document TT 73/95.

Bredenkamp, D.B., Botha, L.J., Van Tonder, GJ, Van Rensburg, H.J. 1995. Manual on Quantitative Estimation of Groundwater Recharge and Aquifer Storativity. Water Research Commission, Pretoria.

CGWB (1997) Report of the Ground Water Resource Estimation Committee-Ground water resource estimation methodology 1997. Central Ground Water Board, Ministry of Water Resources, Govt. of India, New Delhi 107p.

CGWB (2009) Report of the group for suggesting new and alternate methods of ground water resources assessment, Central Ground Water Board, Ministry of Water Resources, Govt. of India, Faridabad, 26p.

Chand R, Hodlur GK, Praksash MR, Mondal NC and Singh VS (2005) Reliable natural recharge estimates in granitic terrain. Current Science, Vol. 88, No.5, pp. 821-824.

Chandrasekharan H, Navada SV, Jain SK, Rao SM and Singh SP (1988) Study on natural recharge to the ground water by isotope techniques in arid western Rajasthan, India, in Simmes I (*ed*) Estimation of natural recharge of ground water: North Atlantic Treaty Organisation, Advanced Science Institute Series, v. 222, p. 205-220.

Childs EC (1969) An introduction to the physical basis of soil water phenomena. Wiley, London

Chong SK, Green RE, Ahuja LR (1981) Simple in-situ determination of hydraulic conductivity by power function descriptions of drainage. Water Resour Res 17:1109–1114

Christophersen N, Hooper RP (1992) Multivariate analysis of stream water chemical data: the use of principal components analysis for the end-member mixing problem. Water Resour Res 28:99–107

Constantz J, Thomas CL, Zellweger G (1994) Influence of diurnal variations in stream temperature on streamflow loss and groundwater recharge. Water Resour Res 30:3253–3264

Cook PG, Herczeg AL, McEwan KL (2001) Groundwater recharge and stream baseflow, Atherton Tablelands, Queensland. CSIRO Land Water Tech Rep 08/01

Cook PG, Solomon DK (1997) Recent advances in dating young groundwater: chlorofluorocarbons, 3H/3He and 85Kr. J Hydrol 191:245–265

Custodio E, Llamas MR, Villarroya F (1998) The role of the Spanish Committee of the International Association of Hydrogeologists in the management and protection of Spain’s groundwater resources Hydrogeology Journal 6:15–23

Cook PG, McEwan KL, Marvanek S (2002) 'Groundwater recharge in the Murray-Darling Basin rangelands - a scoping study.' Murray-Darling Basin Commission, CSIRO Technical Report.

Crosbie RS, McCallum JL, Walker GR and Chiew FHS (2008) Diffuse groundwater recharge modelling across the Murray-Darling Basin. A report to the Australian government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. 108pp.

CSIRO (2007a) Overview of Project Methods, A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. 1-12

CSIRO (2007b).Water availability in the Namoi.A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. 154pp

Connolly RD, Carroll C, Frances J, Silburn DM, Simpson B, Freebairn DM (1999) A simulation study of erosion in the Emerald Irrigation Area. *Australian Journal of Soil Research* 37, 479-494.

Davis S N, Thompson G M, Bentley H W and Stiles G (1980) Ground-water tracers-A short review, Ground water Vol 18, No.1 pp.14-23

Domenico P (1972) Concepts and models in groundwater hydrology. McGraw-Hill, New York.

Environment Agency.Catchment abstraction management strategies (CAMS). www.environment-agency.gov.uk.

deVries JJ, Simmers I (2002) Groundwater recharge: an over--view of processes and challenges. Hydrogeol J 10: DOI 10.1007/s10040-001-0171-7

Dreiss SJ, Anderson LD (1985) Estimating vertical soil moisture flux at a land treatment site. Ground Water 23:503–511

Drost W, Moser H, Neumaier f and Rauert W (1974) Isoope methods in ground water hydrology, Eurisotop Monograph 16, Brussels, pp. 89-97

Dharmasiri, Jaya K. (Year Not known) Further Studies on Tritium Tracing of Soil Moisture for Rainwater Infiltration Measurements in Gatton, Queensland, Australia. http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/30/057/30057781.pdf

Dugan, J.T., and Peckenpaugh, J.M., 1985. Effects of climate, vegetation, and soils on consumptive water use and groundwater recharge to the Central Midwest Regional Aquifer System, Mid-Continent United States. U.S. Geological Survey Water Resources Investigations Report 85-4236, 78 p.

Dugan, J.T. and Zelt, R.B. 2000.Simulation and analysis of soil-moisture conditions in the Great Plains and adjacent areas. 1951-80. US Geological Survey Water Supply Paper 2427.

Dalal RC, Mayer RJ (1986) Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. I Overall changes in soil properties and trends in winter cereal yields. *Australian Journal of Soil Research* 24, 265-279.

Dalal RC, Strong WM, Weston EJ, Cooper JE, Lehane KJ, King AJ, Chicken CJ (1995) Sustaining productivity of a Vertisol at Warra, Queensland, with fertilisers, no-tillage or legumes. 1. Organic matter status. *Australian Journal of Experimental Agriculture* 35, 903-913.

Engman ET, Gurney RJ (1991) Remote Sensing in Hydrology. Chapman and Hall, London.

Eriksson E, Khunakasem V (1969) Chloride concentration in groundwater, recharge rate and rate of deposition of chloride in the Israel Coastal Plain. J Hydrol 7:178–197

European Commission. 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Off J Euro Commun, L 327.

Enslin, JF (1970). Die grondwaterpotensiaal van Suid-Afrika. Convention Water for the Future, Pretoria, Nov.1970.

Freeze RA (1971) Three-dimensional, transient, saturated-unsaturated flow in a groundwater basin. Water Resour Res 7:347–366

Freeze RA, Cherry JA (1979) Groundwater. Prentice-Hall.

Farnsworth RK, Barret EC, Dhanju MS (1984) Application of remote sensing to hydrology including ground water. IHP-II Project A. 1.5, UNESCO, Paris, France

Ferguson, G., A.D. Woodbury, and G.L.D. Matile. 2003. Estimating deep recharge rates beneath an interlobate moraine using temperature logs. Ground Water 41, no. 5: 640–646.

Flint AL, Flint LE, Kwicklis EM, Fabryka-Martin JT, Botrarsson GS (2002) Estimating recharge at Yucca Mountain, Nevada, USA: comparison of methods. Hydrogeol J 10: DOI 10.1007/s10040-001-0169-1

Freeze RA and Cherry JA (1979) Groundwater. Prentice Hall, Inc. Englewood Cliffs, New Jersey, 604p.

Frenzel, S. A. (1985). Comparison of Methods for Estimating Groundwater Pumpage for Irrigation.Journal of Groundwater, 23(2): 220-226.

Fitzsimons, V.P., Misstear, B.D.R. 2006.Estimating groundwater recharge through tills: a sensitivity analysis of soil moisture budgets and till properties in Ireland.Hydrogeology Journal. 14. pp. 548 – 561

Fu BP 1981, On the calculation of the evaporation from land surface (in Chinese), *ScientiaAtmosphericaSinica*5, 23–31.

Gutentag, E.D., Lobmeyer, D.H. and Slagle,S.E. 1981. Geohydrology of southwestern Kansas.Kansas Geological Survey Irrigation Series 7.

Goode AM and Barnett BG (2008) Southern Riverine Plains Groundwater Model Calibration Report. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. 138pp.

Goode AM and Daamen CC (2008) Mid-Murrumbidgee Groundwater Model Calibration Report. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. 40pp.

Gardner WR (1964) Water movement below the root zone. In: Proc 8th IntCongr Soil Sci, Bucharest, 31 Aug–9 Sept, Rompresfilatelia, Bucharest, pp 317–320

Gat JR and Gonfiantini (1981) Stable isotope hydrology: deuterium and oxygen-18 in the water ccyle. Tech Rep Ser N. 210, IAEA, Vienna.

Gates J B, Edmunds WM, Ma J and Scanlon BR. (2008) Estimating groundwater recharge in a cold desert environment in northern China using chloride Hydrogeology Journal. Vol. 16, pp. 893–910.

Gieske A, De Vries JJ (1990) Conceptual and computational aspects of the mixing-cell method to determine groundwater recharge components. J Hydrol 121: 277–292

Garcia-Fresca B (2005) Urban-enhanced groundwater recharge: review and case study of Austin, Texas, USA BGF DRAFT - 32 IGC - Matthias Eiswirth Memorial Volume pp.1-14

Hatton T (1998) Catchment scale recharge modelling. Part 4 of The basics of recharge and discharge. CSIRO, Collingwood, Victoria

Healy RW, Cook PG (2002) Using groundwater levels to estimate recharge. Hydrogeol J 10: DOI 10.1007/s10040-001-0178-0

Healy RW, Gray JR, de Vries MP, Mills PC (1989) Water balance at a low-level radioactive disposal site. Water Resour Bull 25:381–390

Hillel D (1980) Fundamentals of soil physics. Academic Press, London

Hooper RP, Christophersen N, Peters NE (1990) Modeling of streamwater chemistry as a mixture of soilwaterendmembers – an application to the Panola Mountain catchment, Georgia, USA. J Hydrol 116:321–343

Hsieh PA, Wingle W, Healy RW (2000) VS2DI – a graphical software package for simulating fluid flow and solute or energy transport in variably saturated porous media. US GeolSurv Water-Resour Invest Rep 99–4130:16

Hulme P, Rushton KR, Fletcher S (2001) Estimating recharge in U.K. catchments. In: Impact of human activity on groundwater dynamics. International Association Hydrological Sciences Publ 269:33–42

Hansen, C.V. 1991. Estimates of freshwater storage and potential natural recharge for principal aquifers in Kansas. U.S. Geological Survey,Water-Resources Investigations Report 87-4230.

Hsu TL (1961) Investigation report on groundwater resource of the Pingtung Plain. Provincial Groundwater Development Bureau, Taiwan, 150 pp

Huxley W (1982) Condamine River Valley Groundwater Investigation.The Hydrogeology, Hydrology & Hydrochemistry of the Condamine River Valley Alluvium.Volume 1 (text).Queensland Water Resources Commission – Groundwater Branch.

Hawthorne K 2006 A Methodology for Estimating Regional Agricultural Water Use Australian Bureau of Statistics, research paper- 4616.0.55.001. 21p

Healy, R.W., Winter, T.C., LaBaugh, J.W., and Franke, O.L., 2007, Water budgets—Foundations foreffective water-resources and environmental management: U.S. Geological Survey Circular 1308, 90 p.

Israil M, al-hadithi M, Singhal DC and Kumar B (2006) Ground water recharge estimation using a surface electrical resistivity method in the Himalayan foothill region, India. Hydrogeology Journal 14:44-50.

Jackson TJ (2002) Remote sensing of soil moisture: implications for groundwater recharge. Hydrogeology Journal 10:40-51.

Jones HK and Cooper JD (1998) Water transport through the unsaturated zone of the Middle Chalk: a case study from Fleam Dyke lysimeter. In: Groundwater pollution, aquifer recharge and vulnerability, Robins, N. (*ed.*). Geological Society of London Special Publication.

Jolly ID (1989) Investigation into the potential for increased stream salinisation in the Darling Basin. Centre for Research in Groundwater Processes, Report No. 10.

Jin M, Liang X, Simmers I, Gao Y, Zhang R. 2000. *Estimation of Groundwater Recharge Using Artificial Tritium Tracing*. China Environmental Science Press: Wuhan; 340–345.

Kalf, Frans R. P. and Woolley, Donald R.. 2005. Applicability and methodology of determining sustainable yield in groundwater systems. *Hydrogeol J* (2005) 13:295–312.

Kromm, D.E., and White, S.E., 1992. Groundwater problems. In: Kromm, D.E. and White, S.E., (eds.), Groundwater Exploitation in the High Plains. University of Kansas Press, Lawrence, KS, p. 44-63.

Kendy E, Gerard-Marchant P, Walter MT, Zhang Y, Liu C, Steenhuis TS. 2003. A soil-water-balance approach to quantify groundwater recharge from irrigated cropland in the North China Plain. *Hydrological Processes* 17: 2011–2031.

Kendy E, Zhang Y, Liu C, Wang J, Steenhuis T. 2004. Groundwater recharge from irrigated cropland in the North China plain: case study of Luancheng County, Hebei Province, 1949–2000. *Hydrological Processes* 18: 2289–2302.

Khan MA and Sharma M (2003) Estimation of ground water potential in Indian arid environment using isopach mapping technique: a case study, Journal Geological Society of India, vol. 61, pp.403-410.

Lee CH (1915) The determination of safe yield of underground reservoirs of the closed basin type. Trans Am Soc Civil Eng 78:148–151.

Lapham WW (1989) Use of temperature profiles beneath streams to determine rates of vertical groundwater flow and vertical hydraulic conductivity. US GeolSurv Water-Supply Pap 2337:35

Leavesley GH, Stannard LG (1995) The precipitation–runoff modeling system – PRMS. In: Singh VP (ed) Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, Colorado, pp 281–310

Lerner DN (1997) Groundwater recharge. In: Saether OM, de Caritat P (eds) Geochemical processes, weathering and groundwater recharge in catchments. AA Balkema, Rotterdam, pp 109–150

Lerner DN (2002) Identifying and quantifying urban recharge: a review. Hydrogeol J 10: DOI 10.1007/s10040-001-0177-1

Luckey, R.L., Gutentag, E.D.,Hiemes, F.J. and Weeks, J.B. 1986. Digital simulation of groundwater flow in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming, U.S. Geological Survey Professional Paper 1400-D.

Lawrence PA, Cowie BA, Yule D, Thorburn PJ (1993) Water balance and soil fertility characteristics of brigalow (*Acacia harpophylla*) lands before and after forest clearing.In 'Proceedings of the XVII International Grassland Congress'.Palmerston North. pp. 2242-2244. (New Zealand Grassland Association: New Zealand)

Lawrence PA, Thorburn PJ, Littleboy M (1991) Changes in surface and subsurface hydrology after clearing Brigalow (Acacia harpophylla) forest in a semiarid climate: measurements and modelling. In 'International Hydrology and Water Resources Symposium'. Perth. Institute of Engineers Australia National Conference Publication 91/22. pp. 374-380. (Institute of Engineers Australia)

Lee CH, Chen WP and Lee RH (2006) Estimation of groundwater recharge using water balance coupled with baseflow record estimation and stable base flow analysis. Environmental Geology, Vo. 51 pp. 73:82

Lin YT (1986) Information on land subsidence in coastal areas of Taiwan: a collection of papers on irrigation drainage and engineering in Taiwan. Agricultural Engineering Research Center, Chungli, Taiwan, pp 927–953

Luckey, R.L., and Becker, M.F., 1999. Hydrogeology, water use, and simulation of flow in the High Plains aquifer in northwestern Oklahoma, southeastern Colorado, southwestern Kansas, northeastern New Mexico, and northwestern Texas. U.S. Geological Survey Water-Resources Investigations Report 99-4104, 68 p.

Ministry of Water Resources (2002) National Water Policy, Ministry of Water Resources, Government of India, New Delhi.

Meijerink AMJ (2000) Groundwater. In: Schultz GA, Engman ET (*eds*) Remote Sensing in hydrology and water management, Springer, Berlin Heidelberg New York, pp. 305-325.

Munnich KO (1968) Use of nuclear techniques for the determination of ground water recharge rates. *in* Guide book on nuclear techniques in hydrology, IAEA, Vienna pp. 191-197.

McGuinness, C.L., 1951, The water situation in the United States with special reference to ground water: U.S. Geological Survey Circular 114, 127 p.

McGuinness, C.L., 1963, The role of ground water in the national water situation: U.S. Geological Survey Water-Supply Paper 1800, 1,121 p.

Meinzer, O.E., 1923, The occurrence of ground water in the United States with a discussion of principles: U.S. Geological Survey Water-Supply Paper 489, 321 p.

Maupin, M.A., and Barber, N.L., 2005, Estimated withdrawals from principal aquifers in the United States, 2000: U.S. Geological Survey Circular 1279, 46 p.

McDonald, M.G. and Harbaugh, A.W. 1988. A modular three-diamentional finite difference groundwater flow model.US Geological Survey Open-file Report 83-875.

Meyer, W.R., Grover, B.L. and Carlson,G.W. 1953. 1952 irrigation experiments U.S. Department of Agriculture Soil Conservation Service Reserch.

Meyer, W.R., Gutentag, E.D. and Lobmeyer, D.H. 1970. Geohydrology of Finney County, southwestern Kansas.U.S. Geological Survey Water Supply Paper 1891.

Ma JZ, Ding Z, Gates JB, Su Y 2008 Chloride and the environmental isotopes as the indicators of the groundwater recharge in the Gobi Desert, northwest China. Environ Geol vol. 55, pp.1407–1419

Ma J, Edmunds WM (2006) Groundwater and lake evolution in the BadainJaran desert ecosystem, Inner Mongolia.Hydrogeol J 14 (7):1231–1243

Misstear BDR. 2000. Groundwater recharge assessment: a key component of river basin management. In: River basin management, Proceedings, National Hydrology Seminar, Tullamore, 2000, pp 52–59

Misstear, B.D.R., Brown, L. and Daly, D. 2009a. A methodology for making initial estimates of groundwater recharge form groundwater vulnerability mapping. Hydrogeology Journal. 17. 275 – 285.

Misstear, B.D.R., Brown, L. and Johnston, P.M. 2009b. Estimation of groundwater recharge in a major sand and gravel aquifer in Ireland using multiple approaches. Hydrogeology Journal. 17. 693-706.

McNeilage C (2006) Upper Namoi Groundwater Flow Model.Model development and calibration. NSW Dept. of Natural Resources. Parramatta. June 2006.

MDBC (undated) Murray Darling Basin Grond water: a resource for the future Murray Darling Basin Commission Canberra, 31P.

Merrick jN (2001b) Upper Namoi Zone 8 Groundwater flow model: calibration 1979-2000. Report for NSW Dept. of Land and Water Conservation.

Merrick jNP (2001a) Report on Lower Namoi Groundwater Flow Model: Calibration 1980-1998. Insearch Limited Report for Department of Land and Water Conservation. Project Number C99/44/001, July 2001.

Moss J, Gordon I, Zischke R (2001a) 'Best management practices to minimise below root zone impacts of irrigated cotton (Project 16064). Final Report to the Murray-Darling Basin Commission.' Brisbane, Queensland.

Moss J, Gordon I, Zischke R (2001b) 'Delineation of potential salinity hazard areas in Queensland cropping lands.' Department of Natural Resources and Mines, Indooroopilly, Queensland, QNRM01297.

McMahon TA and Mein RG (1978) Reservoir capacity and yield.Developments in water science.Elsevier.

Maupin, M.A., and Barber, N.L., 2005, Estimated withdrawals from principal aquifers in the United States, 2000: U.S. Geological Survey Circular 1279, 46 p.

Nair AR, NAVADA SV and Rao SM (1978) Isotope tracer techniques for soil moisure movement in semi-arid regions-some field experiments, *in* Gupta SK and Sharma (*eds*), Current trends in arid zone hydrology: Conference on Current Trends in Arid Zone Hydrology, Ahmedabad, India, pp.171-182.

Nathan RJ, McMahon TA (1990) Evaluation of automated techniques for base flow and recession analyses. Water Resour Res 26:1465–1473

Nace, R.L., 1960, Water management, agriculture, and ground-water supplies: U.S. Geological Survey Circular 415, 12 p.

Ponce, Victor M. 2007. Sustainable yield of ground water. http://gwsustainability.sdsu.edu.

Seward, P., Y. Xu, and L. Brendock. (2006). Sustainable groundwater use, the capture principle, and adaptive management. Water SA, Vol. 32, No. 4, October, 473-482.

Payne BR and Halevy E 1968 Guide book on nuclear techniques in hydrology,Vienna, IAEA.

Phillips FM (1994) Environmental tracers for water movement in desert soils of the American Southwest. Soil SciSoc Am J 58:14–24

P.E. Tolmie, D.M. Silburn, A.J.W. Biggs 2004Estimating deep drainage in the Queensland Murray-Darling Basin using soil chloride Department of Natural Resources and Mines, Toowoomba, 47p

Petheram C, Zhang L, Walker G, Grayson R (2000) 'Towards a framework for predicting impacts of land-use on recharge: A review of recharge studies in Australia'. CSIRO Land and Water, Technical Report 28/00, Canberra ACT.

QMDCC (1998) Natural Resources Management Strategy for the Queensland Murray-Darling Basin. Queensland Murray-Darling Basin Coordinating Committee, Queensland Department of Natural Resources, Queensland Department of Environment. DNRQ980018.

Rejman W (2007) EU Water Framework Directive versus real needs of groundwater management water resources management 21:1363–1372

Rangarajan, R. and Athavale, R. N. (2000). Annual replenishable ground water potential of India- an estimate based on injected tritium studies. Journal of hydrology, 234: 38-53.

Rao SM (1983) Use of radioactive tracers in studies on infiltration through unsaturated zone: tracer methods in isotope hydrology, IAEA Vienna (IAEA-TECDOC-291), pp.47-66.

Rao SVN, Vijay Kumar SV, Saheb SM and Ramasastri KS (2004) Regional estimation of draft and recharge for coastal aquifers using heuristic optimization algorithms. IE(I) Journal –CV vol. 85, pp.8-16

Rao, S. V. N., VijayaKumar, S. V., Saheb, S. M. and Ramasastri, K. S. (2004).Regional estimation of draft and recharge for coastal aquifers using heuristic algorithms. IE (I) journal-CV, 85:8-16.

Ray RK and Thambi DS (2003) Discussion on estimation of ground water potential in Indian arid environment using isopach mapping technique: a case study. Journal Geological Society of India.Vol 62, pp. 382-383.

Richards LA, Gardner WR, Ogata G (1956) Physical processes determining water loss from soil. Soil SciSoc Am Proc 20:310–314

Rodell M, Famiglietti JS (1999) Delectability of variations in continental water storage from satellite observations of the time dependent gravity field. Water Resour Res 35:2705–2723

Rodell M, Famiglietti JS (2001) An analysis of terrestrial water storage variations in Illinois with implications for the Gravity Recovery and Climate Experiment (GRACE) gravity field. Water Resour Res 37:1327–1339

Rodell M, Velicogna I and Famiglietti JS (2009) Satellite-based estimates of groundwater depletion in India, Nature, Vol. 460, pp.999-1002

Ronan AD, Prudic DE, Thodal CE, Constantz J (1998) Field study and simulation of diurnal temperature effects on infiltration and variably saturated flow beneath an ephemeral stream. Water Resour Res 34:2137–2153

Rorabough MI (1964) Estimating changes in bank storage and groundwater contribution to streamflow. IntAssocSci Hydro Publ 63:432–441

Rosenberg NJ, Blad BL, Verma SV (1983) Micro-climate: the biological environment, 2nd edn. Wiley, New York

Royer JM, Vachaud G (1974) Determination directe de l'evapotranspirationet de l'infiltration par mesures des teneurs en eau et des succions. HydrolSci Bull 19:319–336

Rushton KR (1988) Numerical and conceptual models for recharge estimation in arid and semi-arid zones. In: Simmers I (ed) Estimation of natural groundwater recharge. NATO ASI Series C 222. Reidel, Dordrecht, pp 223–238

Reilly, T.E., Dennehy, K.F., Alley, W.M. and Cunningham, W.L. 2008. Ground-Water Availability in the United States: A contribution of the Ground-Water Resources Program. USGS: Circular 1323.

Richardson S, Walker GR, Barnett B, Daamen C, Davies P, Evans RS, Evans WR, Goode A, Pritchard J and Waklawik V (2008) Groundwater management unit prioritisation and assessment ranking. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia. 33pp.

Rose CW, Dayananda DR, Nielsen DR, Biggar JM (1979) Long-term solute dynamics, hydrology in irrigated slowly permeable soils.*Irrigation Science* 1, 77-87.

Ruifen L, Keqin W. 2001. Environmental isotope profiles of the soil water in loess unsaturated zone in semi-arid areas of China. In *Isotope Based Assessment of Groundwater Renewal in Water Scarce Regions*, IAEA Tecdoc-1246, Yurtsever Y (ed.). IAEA: Vienna, 101–118.

Raupach MR, Kirby JM, Barrett DJ, Briggs H, Lu H and Zhang L 2001, 'Balances of water, carbon, nitrogen and phosphorus in Australian Landscapes: (2) Model formulation and testing', Technical Report 41/01, CSIRO Land and Water.

Roy, S.B., Ricci, P.F., Summers, K.V., Chung, C.F., and Goldstein, R.A., 2005, Evaluation of the sustainability of water withdrawals in the United States, 1995 to 2025: Journal of the American Water Resources Association, v. 41, no. 5, p. 1091–1108.

Sophocleous M (1997) Managing water resources systems: why safe yield is not sustainable. *Ground Water*. 35(4):561

Sophocleous M (ed) (1998) Perspectives on sustainable development of water resources in Kansas. Geol Sur Bull, Kansas 239

Sophocleous M (2000) From safe yield to sustainable development of water resources: the Kansas experience. *J Hydrol* 235:27–43.

Saha D and Agrawal AK (2006). Determination of specific yield using a water balance approach-case study of TorlaOdha watershed in the Deccan Trap province, Maharastra State, India. Hydrogeology Journal 14: 625-635.

Sanford W (2002) Recharge and groundwater models: an overview. Hydrogeol J 10: DOI 10.1007/s10040-001-0173-5

Scanlon BR (1991) Evaluation of moisture flux from chloride data in desert soils. J Hydrol 128:137–156

Scanlon BR (2000) Uncertainties in estimating water fluxes and residence times using environmental tracers in an arid unsaturated zone. Water Resour Res 36:395–409

Scanlon BR, Healy RW, Cook PG (2002) Choosing appropriate techniques for quantifying groundwater recharge.Hydrogeol J 10: DOI 10.1007/s10040-001-0176-2

Schicht RJ, Walton WC (1961) Hydrologic budgets for three small watersheds in Illinois. Ill State Water Surv Rep Invest 40:40

Scozzafava M and Tallini M (2001) Net infiltration in the Gran Sasso Massif of central Italy using the Thornthwaite water budget and curve-number method Hydrogeology Journal 9:461–475

Simmers I (ed) (1988) Estimation of natural groundwater recharge. Reidel, Boston, 510 pp

Simunek J, Sejna M, van Genuchten MT (1996) Hydrus-2D: simulating water flow and solute transport in two-dimensional variably saturated media. International Groundwater ModelingCenter, Colorado School of Mines, Golden, Colorado

Sisson JB (1987) Drainage from layered field soils: fixed gradient models. Water Resour Res 23:2071–2075

SophocleousM(1985) The role of specific yield in groundwater recharge estimations: A numerical study. Groundwater, 23:52-58.

Stallman RW (1964) Multiphase fluid flow in porous media – a review of theories pertinent to hydrology studies. US GeolSurv Prof Pap 411-E:51

Stallman, R.W. 1965. Steady one-dimensional fluid flow in a semi-infinite porous medium with sinusoidal surface temperature. Journal of Geophysical Research 70, no. 12: 2821–2827.

Stothoff SA (1995) BREATH Version 1.1 – coupled flow and energy transport in porous media, simulator description and user guide. Publ NUREG/CR-6333. US Nuclear Regulatory Commission, Washington, DC

Sukhij BS, Reddy DV, Nagabhushanam P and Chand R (1988) Validity of the environmental chloride method for recharge evaluation of coastal aquifers, India. Journal of Hydrology, 99:349-366

Sukhija BS, Reddy, DV, Nagabhushanam P and Hussain S (2003) Recharge processes: piston flow vs preferential flow in semi-arid aquifers of India. Hydrogeology Journal 11:387-395

Sukhija BS, Shah CR (1976) Conformity of ground water recharge rate by tritium method and methamaticalmodeling. Journal of Hydrology 30:167-178.

Suzuki, S. 1960. Percolation measurements based on heat flow through soil with special reference to paddy fields. Journal of Geophysical Research 65, no. 9: 2883–2885.

Swenson S, Wahr J (2006) Post-processing removal of correlated errors in GRACE data, Geophys Res Lett 33:L08402. DOI 10.1029/2005GL025285

Schloss, J.A., Buddemeier, R.W., and Wilson, B.B. (eds.), 2000.An atlas of the Kansas High Plains aquifer. Kansas Geological Survey Educational Series 14, 92 p.http://www.kgs.ku.edu/HighPlains/atlas.html

Sophocleous, M.A., 2000a. From safe yield to sustainable development of water resources —the Kansas experience. Journal of Hydrology, 235(1-2): 27-43.

Sophocleous, M.A., 2000b. The origin and evolution of safe yield policies in the Kansas Groundwater Management Districts. Natural Resources Research, 9(2): 99-110.

Sophocleous, Marios. 2003. Groundwater Recharge and Water Budgets of the Kansas High Plains and related aquifers. Kansas Water Resources Institute.

Sophocleous M. 2009. Review: groundwater management practices, challenges, and innovations in the High Plains aquifer, USA—lessons and recommended actions. Hydrogeology Journal.Online publication. DOI:10.1007/s10040-009-0540-1

Shaw RJ, Thorburn PJ (1985) Prediction of leaching fraction from soil properties, irrigation water and rainfall.*Irrigation Science* 6, 73-83.

Silburn DM, Freebairn DM (1992) Evaluation of the CREAMS model. III. Simulation of the hydrology of vertisols. *Australian Journal of Soil Research* 30, 547-564.

Silburn DM, Montgomery J (2004) Deep drainage under irrigated cotton in Australia: a review. In 'WATER-PAK a guide for irrigation management in cotton'. pp. 29-40. (Cotton Research and Development Corporation/Australian Cotton Cooperative Research Centre: Narrabri)

SKM (1999) Conjunctive Water Use Study – Upper Condamine River Interim Report. Prepared for Murray-Darling Basin Commission, Department of Natural Resources, Darling Downs Vision 2000. Sinclair Knight Merz, October 1999.

Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmunds WM and Simmers I. (2006) Global synthesis of groundwater recharge in semiarid and arid regions. Hydrological processes, vol 20, pp. 3335–3370

Simonic, M., (2001): Electronic Atlas on National Groundwater Quality Assessment at a nationalscale in the Republic of South Africa, WRC Report 841/1/01, Water Research Commission,Pretoria.

The National Land & Water Resources Audit (NLWRA). 2007. Australian Water Resources Assessment 2000. http://www.anra.gov.au/

Theis, C. V. (1940). The source of water derived from wells: Essential factors controlling the response of an aquifer to development. Civil Engineering, Vol 10, No. 5, May, 277-280.

Todd, D. K. (1959).Ground Water Hydrology.John Wiley and Sons.

Taniguchi, M., J. Shimada, T. Tanaka, I. Kayane, Y. Sakura, Y. Shimano, S. Dapaah-Siakwan, and S. Kawashima. 1999. Disturbances of temperature-depth profiles due to surface climate change and subsurface water flow: 1. An effect of linear increase in surface temperature caused by global warming and urbanization in the Tokyo metropolitan area, Japan. Water Resources Research 35, no. 5: 1507–1517.

Taniguchi, M., J.V. Turner, and A.J. Smith. 2003. Evaluations of groundwater discharge rates from subsurface temperature in Cockburn Sound, Western Australia. Biogeochemistry 66, no. 1–2: 111–124.

Tapley BD, Bettadpur S, Ries JC, Thompson PF and Watkins MM (2004). GRACE measurements of mass variability in the Earth system. Science 305, 503–505.

Theis CV (1937) Amount of ground-water recharge in the Southern High Plains. In: Proc American Geophysical Union Trans 18th Annu Meeting, pp 564–568

Thornthwaite CW, Mather JR (1957) Instructions and tables for computing potential evapotranspiration and the water balance, 5th printing.Vol 10, no 3, CW Thornthwaite Associates, Laboratory of Climatology, Elmer, NJ, USA

Tindall JA, Kunkel JR (1999) Unsaturated zone hydrology for scientists and engineers. Prentice Hall, Upper Saddle River, New Jersey

Trescott, P.C., Pinder, G.F., and Larson, S.P., 1976. Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments. U.S. Geological Survey Techniques of Water Resources Investigations, book 7, ch. C1, 116 p.

Thorburn PJ, Cowie BA, Lawrence PA (1991) Effect of land development on groundwater recharge determined from non-steady chloride profiles. *Journal of Hydrology* 124, 43-58.

Tolmie PE and , Silburn DM, 2004 Estimating deep drainage in the Queensland Murray-Darling Basin Review of past research Department of Natural Resources and Mines Toowoomba, 34p

Ting CS (1993) Groundwater resources evaluation and management studies for the Pingtung Plain, Taiwan. National Science Council, National Pingtung Polytechnic Institute and Faculty of Earth Sciences, Free University, Amsterdam, 87 pp

Ting CS, Kerh T and Liao CJ (1998)Estimation of groundwater recharge using the chloride mass-balance method, Pingtung Plain, Taiwan Hydrogeology Journal vol.6, pp.282–292

USSL (1954) 'Diagnosis and improvement of saline and alkali soils'.US Salinity Laboratory. US Department Agriculture Handbook 60 (USDA)

Van Tonder, G.J. 1992. PC Program SVF to calculate the saturate volumes and recharge of an aquifer on a monthly basis. Unpublished computer program. Institute for Groundwater Studies, UOFS. Bloemfontein

World Commission on Environment and Development (The Brundtland Commission).(1987). Our Common Future. The United Nations, New York. Oxford University Press, Oxford.

Walker GR, Zhang L, Ellis TW, Hatton TJ, Petheram C (2002) Estimating impacts of changed land use on recharge: review of modelling and other approaches appropriate for management of dryland salinity. Hydrogeol J 10: DOI 10.1007/s10040-001- 0181-5

Walker GR, Zhang L, Ellis TW, Hatton TJ, Petheram C (2002) Towards a predictive framework for estimating recharge under different land uses: review of modeling and other approaches. Hydrogeol J (in press). DOI 10.1001/s10040010181-5

Waters P, Greenbaum P, Smart L, Osmaston H (1990) Applications of remote sensing to groundwater hydrology. Remote Sensing Rev 4:223–264

Wellings JR (1984) Recharge of the Upper chalk aquifer at a site in Hampshire, England. J Hydrol 69:259–273

Wood WW, Rainwater KA, Thompson DB (1997) Chemical and isotopic methods for quantifying ground water recharge in a regional semiarid environment. Ground Water 33(3):458-468.

Wood WW, Sanford WE (1995) Chemical and isotopic methods for quantifying ground-water recharge in a regional, semiarid environment. Ground Water 33:458–468

Walker G (1998) 'Using soil water tracers to estimate recharge'. The basics of recharge and discharge 7 (Eds L Zhang and GR Walker) (CSIRO: Collingwood, Victoria)

Walker J, Moore RM, Robertson JA (1972) Herbage response to tree and shrub thinning in Eucalyptus populnea shrub woodlands.*Australian Journal of Agricultural Research* 23, 405-410.

Willis TM, Black AS (1996) Irrigation increase groundwater recharge in the Macquarie Valley. *Australian Journal of Soil Research* 34, 837-847.

Working Group on Groundwater. 2005. Water Framework Directive (WFD) Pressures and impacts assessment methodology: guidance on the assessment of the impact of groundwater abstractions. Geological Survey of Ireland, Environmental Protection Agency and River Basin Districts Coordinating Authorities, Dublin.

Working Group on Groundwater. 2008. National recharge map of Ireland. Geological Survey of Ireland, Environmental Protection Agency and River Basin Districts Coordinating Authorities, Dublin.

Wang XP, Berndtsson R, Li XR, Kang ES.2004a. Water balance change for a re-vegetated xerophytes shrub area.*Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*49: 283–295.

Water Resources Agency (2003) Ground water resource map of Taiwan, Republic of China (in Chinese).Taiwan Water Resource Agency, Ministry of Economic Affairs Report, 110p.

Water Affairs and Forestry Department (2006) Methodology for groundwater quantification. GRA II Task – 1A, 1BC, 1D.

Water Affairs and Forestry Department (2006) Groundwater Planning Potential. GRA II Task – 2A, 2B, 2C.

Water Affairs and Forestry Department (2006) Recharge. GRA II Task – 3aA, 3aB, 3aC, 3aD, 3aE.

Water Affairs and Forestry Department (2006) Classification. GRA II Task – 4A, 4B.

Wolock, D.M., 2003a, Estimated mean annual natural ground-water recharge in the conterminous United States: U.S. Geological Survey Open-File Report 03–311, digital dataset, accessed on November 20, 2007, at http://water.usgs.gov/lookup/getspatial?rech48grd.

Wolock, D.M., 2003b, Base-flow index grid for the conterminous United States: U.S. Geological Survey Open-File Report 03–263, digital dataset, accessed on November 20, 2007, at http://water.usgs.gov/lookup/getspatial?bfi48grd

WRON (2006) Australian Water Resources 2005-Discovery phase, Appendix C Theme report: Ground water. 152p.

Water Affairs and Forestry Department (2006) Groundwater Use. GRA II Task – 5A, 5B, 5C, 5D, 5E.

WSM Civil Engineers, Hydrogeologists& Project Managers (Pty) Ltd (2001) Water resources assessment. Director of Water Resource Planning.Department of Water Affairs and Forestry. Groundwater resource of South Africa

Xu, Y and Beekman, HE (Eds), 2003.Groundwater recharge estimation in Southern Africa. UNESCO IHP Series No. 64, UNESCO Paris.ISBN 92-9220-000-3.

Xu, Y. and van Tonder, G.J., 2001. Estimation of recharge using a revised CRD method. Water SA, Vol.27, No. 3, 341-343.

Xu, Yongxin and Beekman, Hans E. (2003) Groundwater Recharge Estimation in Southern Africa. UNESCO International Hydrological Programme (IHP). Paris.

Young R, McLeod M (2001) Estimation of historic deep drainage under grassed woodland, Lucerne pastures and cropped paddocks in the upper Liverpool Plains catchment using the SODICS model. pp 107-110. In ‘Update of research in progress at the Tamworth Centre for Crop Improvement 2001.’(Ed. Bob Martin). (NSW Agriculture: Tamworth).

Yan M, Wang S, Li B, Dong G (2001) Formation and growth of high mega dunes in BadainJaran Desert. ActaGeogr Sin 56:83–91

Yang et al. Large lysimeter.

Yeh HF, Lee CH, Chen JF and Chen WP, 2007. Estimation of ground water recharge using water balance model. Water Resources vol. 34, no. 2 pp. 171-180

Zimmermann U, Ehhalt D and Munnich KO (1967a) Soilwater movement and evapotranspiration; changes in isotope composition of the water. IN: Isotopes in Hydrology, IAEA, Vienna, pp. 567-586.

Zimmermann U, Munnich KO and Roether W (1967b) Downward movement of soil moisture traced by means of hydrogen isotopes. GeophysMonogr Am Geophys Union 11:28-36.

Zhang L, Dawes W (1998) WAVES - An Integrated Energy and Water Balance Model. Technical Report No. 31/98, CSIRO Land and Water.

Zhang L, Hickel K and Shao Q 2006 ‘Water balance modeling over variable time scales’, *MODSIM Conference*, December 2005, Melbourne.

Zhang L, Hickel K, Dawes WR, Chiew FHS, Western AW and Briggs PR 2004, ‘A rational function approach for estimating mean annual evaporation’, *Water Resources Research*, 40.

Central Ground Water Board (CGWB), Bujal Bhawan, NH-IV, Faridabad, Haryana.
www.cgwb.gov.in, res-cgwb@nic.in, +91 129 2477123, 2477129 (Fax)