11. Techniques for Estimating Groundwater Recharge at Different Scales in Southern Africa

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ABSTRACT Various applied techniques for estimating ground water recharge are described for local, hillslope, catchment, regional and national scales. It is clear that the scale of the problem being investigated must determine the method used. Recharge estimates are generally performed assuming a vertical profile. However, it is also evident that the hillslope and lateral processes inherent in generating event and low flow discharges must be defined and quantified so that the proper streamflow generating source, whether ground water aquifer or hillslope vadose zone, is identified. From this knowledge will emanate adequate quantification of ground water recharge mechanisms and rates.

11.1 Introduction

The definition of what constitutes the ground water recharge component in the hydrological cycle is often difficult and could easily depend on the perspective of the scale at which the process is observed. While a basin study of water resources may define the recharge component as the useable resource from a large aquifer, a user of a rural well may define the recharge as that component of interflow and percolation which replenishes the well's source during an irrigation season. Since the demand for localised sources of ground water, as well as regional catchment management are both pressing issues, methods for quantifying the recharge process at different scales are examined so that appropriate methods may be used for the quantification of recharge for specific purposes.

A number of techniques which quantify the recharge process at different scales are presented in this paper. We examine the local or (point scale), the hillslope scale, the catchment scale as well as regional and national scales.

11.2 Local Scale

Local scale recharge has been estimated using a daily hydrological water budget model, ACRU (Schulze, 1995). The processes and water volume accounting shown in Figure 11.1 have been used successfully to model the daily stormflow and baseflow throughout southern Africa at specific locations. The recharge to ground water has mostly been taken as that volume of water which is depleted from the subsoil and is added to the intermediate and ground water store below. While this water budgeting method may be appropriate for estimating the average diffuse discharge from the subsoil in typical profiles, this simplified method of estimating the volume of water recharging the ground water may not be appropriate for specific scenarios where hydraulic potentials and soil and ground water flux variations control the movement of water into an aquifer.

The simplification of the subsoil-ground water interaction used in ACRU, shown in Figure 11.2a, relies on user-defined parameters for apportioning the volumes of water allocated to the different horizons each day. Although the incremental volumes moving from one horizon to another are predominantly dependent on the storage states (and thus indirectly, hydraulic potentials) of the horizons, the transfer parameters either remain constant or take up predetermined values according to the storage state of the horizons. The physics of the interactions between surface-, soil- and ground water, which may play a predominant role in the recharge process is not always adequately simulated in this threshold-based approach. Rapid wetting front development resulting from extreme rainfall events requires a more detailed physically based approach (Gee et al, 1994; Stephens, 1994). Interactions between layers of different hydraulic properties and between capillary forces in the soil and saturated conditions in fractured or dual porosity media also require a revised model since these interactions could easily dominate the recharge process. Estimation of recharge in arid and semi-arid environments could be improved if the dynamics of extreme events were successfully simulated rather than relying on simplified water budgeting.

Attempts at modifying the ACRU soil water budgeting with a Green-Ampt wetting front model have proved successful in simulating the flux through the soil profile in response to rainfall events of different intensity (Lorentz et al., 1995; Howe and Lorentz, 1995). Innovations in applying Richard's equation make this an attractive method for simulating soil water dynamics (Short et al 1995). Considerable improvement in both infiltration and soil water redistribution dynamics has also been achieved in ACRU, with the application of a solution of the Richard's equation in the soil horizons. However, these approaches are always dependant on appropriate boundary conditions at the vadose zone- ground water or fractured media interface. Most early attempts have used a constant head condition at the zero matric pressure elevation, thus requiring a user input of the ground water depth. However the response to the recharge and consequent perturbations in the soil water potentials have been largely ignored.

An attempt to retain the physical basis of subsoil-ground water interaction simulation has been developed in the ACRU model as depicted in Figure 11.2b. The fluxes from one zone to another are modelled using the hydraulic characteristics of the porous media. The water dynamics is modelled in the soil horizons of the vadose zone using Richard's equation. At the interface of the soil horizons and a fractured bedrock, it is recognized that soil matric pressure heads must approach zero before flow is induced into the fractures. Allowance is provided for flux into the fractured bedrock prior to saturation of the soil interface if the bedrock properties allow for capillary flow. Once soil water matric pressures are zero at this interface, flow into the bedrock commences at a rate dependent on the hydraulic properties of the bedrock. Soil water contents may then increase in the soil as shown in Figure 11.2b and positive pressures may develop at the interface, forming a perched water table. Perched water tables may also develop in the soil horizons if clay layers are present.

Distinctly different recharge processes have been simulated in the Romwe experimental catchments near Triangle in Zimbabwe, some 150 km north of Beit Bridge. This modelling was undertaken in collaboration with the Centre for Ecology and Hydrology, Wallingford, who completed extensive monitoring of the recharge processes in these agricultural catchments (Butterworth et al., 1999). Ground water recharge was shown to be strongly controlled by the characteristics of the weathering profile, lending credence to attempts to model the recharge dynamics in semi-arid areas by considering profile hydraulic characteristics and boundary conditions. The Romwe catchments receive a mean annual precipitation of 581 mm with a standard deviation of this mean of 263 mm which is typical of the large interannual variation in semi-arid catchments. Subsistence agriculture is practised on two predominant soil types in the catchment. The first is a red clay with granular microstructure derived from the mafic pyroxene gneiss north of the stream (Figure 11.3). The second is a grey coloured sandy soil of coarse texture underlaid by a thick clay layer. This soil type is associated with the leucocratic gneiss south of the stream. Typical profiles and associated hydraulic conductivity characteristics are shown for the soils in Figures 11.5 and 11.6. The red clay soil has a saturated conductivity an order of magnitude less than the grey sandy soil but the clay which underlies this sandy soil has a saturated hydraulic conductivity an order of magnitude less than that of the red clay soil.

During an event on February 17th 1994, 141 mm of rain was recorded. The resulting recharge to the bedrock estimated from the data is dramatically different for the two horizons as indicated in Table 11.1. The model simulates the runoff and recharge adequately in the two profiles for the event. The recharge for the event was estimated from ground water elevation changes (Figures 11.5 and 11.6) and from hydraulic potentials and conductivities deduced from observed water content changes in the soils at a depth of 2.5 m. The results indicate that the clay layer below the grey sand effectively inhibits recharge while significant recharge occurs through the red clay soil during the week after the event. Agricultural practices may also contribute to the differences in recharge since far more tillage is practised in the heavier red clay surface soils and water retention bunds are often used. The maximum increase in ground water elevation on the north and south side of the stream is shown for the wet season, 1993/94 in Figure 11.4. It is clear that the predominant increases in ground water elevation are associated with the red clay soils overlying the leucocratic gneiss bedrock. It is anticipated that a more detailed simulation of the soil water fluxes will provide improved comparisons with other methods deemed in the past to be more accurate than simplified water budgeting (Allison et al., 1994; Barnes et al., 1994; Robson et al., 1992).

Table 11.1 Recharge estimates for the event of February 17th 1994.

Soil	Rain (mm)	Runoff (mm)		Recharge (mm)		
		Modelled	Measured	Modelled	Estimated from G/W elevation	Estimated from changes in water content at 2.5m
Red clay	141.0	6.2	7.0	20.4	16.0	18.6
Grey sand	141.0	52.8	46.5	0.3	*	0

* Observed ground water elevation increased due to flow from sand layer into unlined piezometer.

11.3 Hillslope Scale

Recharge to ground water occurs as one of the processes in hillslope sections and it is often important to define the travel times and pathways of water sources on a hillslope in order to distinguish between the components of event and low flow water. Lateral fluxes of water can be sufficiently slow and residence times sufficiently long on a hillslope that these sources are able to support low flows during dry periods. It is possible that accumulations from these sources could be mistakenly taken as deep ground water contributions to low flows. This would have serious consequences if the land use on the hillslopes were to change. Although lateral fluxes are assumed in the water budgeting models discussed, a more realistic account of the soil and ground water can be obtained by considering the processes on a hillslope scale (Sami and Hughes, 1993). These processes are being observed in an experimental catchment in the Mondi, North East Cape Forests area. The MAP of the area in which the catchment lies is some 850 mm, which is considered marginal for successful commercial forestry. Therefore, knowledge of the hillslope soil water processes is important to allow management to avoid planting trees in areas which may be continuously waterlogged or in areas which are prone to rapid depletion of infiltrating water. The dynamics of flow on the hillslopes in the experimental catchment have been observed under pristine conditions to determine the hillslope water budget prior to the introduction of trees. Monitoring has continued after the trees were established in 2002, so that the changes in the water distribution on the slopes can be quantified and modelled to predict long-term influences of afforestation on receiving water bodies. The catchment lies in a sequence typical of the Molteno formation with two outcrops of rock at different elevations on the slope.

The catchment topography is shown in Figure 11.7, along with the network of neutron probe access tubes, ground water monitoring piezometers, automatic tensiometers, weirs and profile pits. Hydraulic characteristics of the materials have been measured (Figure 11.8) in order to estimate the fluxes from the various sources. The sources and pathways of water on the hillslopes of the catchment have been identified and quantified from the responses of the observed soils water status (Figure 11.9). Typical response zones have been described as:

- Zone 1: Upper slopes of eastern half of the catchment, where delivery of water in a disconnected near surface macro-pore zone delivers water to bedrock outcrop at the toe of the slope. Soil matric pressure is not continuous between responses in near-surface layers and deeper layers near bedrock. Surface water runoff generation for no more than 20 to 30m upslope contributes to flow at the toe. Slow deep ground water from soil/bedrock interface recharges to toe and to lower slopes and bedrock. All water from this zone is delivered to Zone 2.
- Zone 2: Recharge from upslope zone and infiltrating water raise ground water levels at seepage lines and wetland areas. Some flow in near-surface macro-pores. However, it is normally associated with the resident ground water rising into the macro-pore layers, particularly adjacent to the stream and seepage lines leading to the stream. Some ground water ridging near the stream yields increased hydraulic gradients for short periods during moderate to intense events.
- Zone 3: Near stream surface and near-surface water runoff, dominated by ground water intersecting rapid delivery macro-pore layers.
- Zone 4: Some flow in near-surface macro-pore layers, but mostly due to intersection of soil/bedrock perched water. There is generally soil matric pressure continuity between upper and lower layers. Near the stream, water is delivered through ground water rising into macro-pore layers.
- Zone 5: No perched water tables are evident, even during intense events. Little macro-pore discharge in near-surface layers, even during intense events. Significant wetting to deep horizons with slow delivery of unsaturated water to lower slopes (Lorentz, 2001).

Simulation of the catchment runoff using response functions to describe the volumes and arrival times of the various sources reveals a dominant contribution from near surface macro-pore horizons (Figure 11.10). More complex model development may have to be made where observations of large macro-pore or pipe flow is evident (Nieber and Warner, 1991). Nevertheless, water accumulated on the interface of soil profile and bedrock as well as gravity driven, soil water accumulation contributes to discharge in the stream throughout the winter. These accumulations from many of the upland subcatchments appear sufficient to maintain the low flows observed in the receiving rivers, without having recharged a ground water aquifer

(Lorentz, 2003). The relative contribution to both low flow and event water from hillslope and ground water sources is the subject of a present study in which natural isotopes are used in conjunction with the hydrometric measurements, to identify the contributing sources, pathways and travel times.

11.4 Catchment Scale

The water budget approach depicted in Figure 11.1 has been successfully applied to hydrological studies of catchments up to 50 km^2 although larger basins have been simulated by subdividing them into smaller interlinked and cascading subcatchments (Kienzle et al., 1997). GIS is used to prepare area averaged parameters for input to the model. Since the recharge component is a small proportion of the water budget, estimates of recharge are liable to be compounded by errors in the overall water budget. This approach is, therefore, not always ideal for recharge estimates but since the water budget method is based on simulating physical processes, it is useful for comparative exercises in assessing recharge in areas differing in soil profiles, land uses and rainfall patterns.

The direct estimation of recharge on a catchment scale could well be improved by considering the integration of hillslope processes contributing incremental discharges to the conveying stream. Such approaches are becoming increasingly popular in catchment hydrology and can only contribute to a better understanding and simulation of recharge.

11.5 Regional Scale

Several methods of estimating ground water recharge and discharge for a catchment from streamflow records have been proposed in the literature. Many of these are graphical, subjective and do not necessarily reflect the true nature of either the recharge or discharge. However, the ACRU model is a deterministic model which attempts to physically model small catchment processes in a conceptual-physical manner.

Research into the development of a baseflow decision support system (BFDSS) to strengthen ACRU’s standard water budget’s ground water and streamflow generation routines have been undertaken (Hughes, 1997). By using data from 200 gauging weirs located throughout South Africa, all of which were deemed to be recording natural flow, this research established a link between baseflow recession characteristics and a basin’s physical and geological properties.

Determining multiple segment master recession curves aided in the evaluation of the true shape of the master recession curves (MRC) thereby accounting for McMahon's (1995) suspicion that exponential recession theory would be inappropriate for baseflow recession modelling in South Africa. This was achieved using the procedure summarised in Figure 11.11 where all recessions are extracted (stage A) and eliminated (stage B) if they contain missing or suspect data or if significant rainfall occurs during the recession or if they are of less than 10 days in duration. The remaining data are converted from daily specific to discharge specific data (stage C) to facilitate the calculation of average recession constants for each discharge interval (stage D). These are used to construct the MRCs (stage E).

11.6 National Scale

An extensive database has been developed for hydrological simulations in South Africa by the School of Bioresources Engineering and Environmental Hydrology, University of Natal. Daily rainfall data have been assembled for each of the 1946 quaternary subcatchments in South Africa for the period 1951-1993. GIS techniques have been used to derive representative soils and vegetation parameters for each quaternary subcatchment and files of average monthly potential evaporation and maximum and minimum temperatures have been compiled. The database comprises a powerful resource for estimating components of the hydrological cycle throughout the area, comparison of irrigation supply and demand, crop production performance for different areas as well as for estimating the significance of certain extreme events or trends such as climate change.

Hydrological simulations have been undertaken to estimate the distribution of average annual recharge, as shown in Figure 11.12. The recharge simulated for a wetter than average year (La Nina, 1988/89) is compared with the average annual recharge by displaying the ratios of the recharge for these periods. While the 1988/1989 season produced wetter than average rainfall predominantly in a band from the south-east to the north-west of the country, only a few quaternary subcatchments in this semi-arid zone yield recharge estimates larger than average. Conversely, during a drier than average season, 1982/83, every quaternary subcatchment in the summer rainfall region of the country received drier than average rainfall and yet a significant number of quaternary subcatchments in this region were simulated to have above average recharge for that El Nino year. These simulations indicate that there may be merit in examining more closely the influence of extreme and often localised events and rainfall patterns in the resultant recharge.

11.7 Conclusions

Various applied techniques for estimating ground water recharge have been described. It is clear that the scale of the problem being investigated must determine the method used. It is also evident that the processes inherent in generating event and low flow discharges must be defined and quantified so that the proper streamflow generating source, whether ground water aquifer or hillslope vadose zone, is identified. From this knowledge will emanate adequate quantification of ground water recharge mechanisms and rates.

11.8 References

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