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Estimation of groundwater recharge and discharge across northern Australia

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Abstract:

Groundwater recharge is one of the more difficult components of the hydrological cycle to estimate but one that is becoming increasingly important as Australia turns to groundwater resources for future economic development. Also of concern is groundwater discharge. The extraction of groundwater by pumping inevitably reduces groundwater discharge to rivers where the two are connected. Knowledge of both groundwater recharge and discharge is required for effective management of groundwater resources.

Across northern Australia there are few detailed studies investigating groundwater recharge and discharge and none that have applied three independent estimates across 1.2 million km^2. In this study, groundwater recharge has been estimated by upscaling the results from a 1-D soil-vegetation-atmosphere-transfer (SVAT) model (WAVES) and a chloride mass balance. Groundwater discharge to surface water has been estimated through baseflow separation of gauged stream flow data. The SVAT model was used at a point scale to develop relationships between rainfall and recharge for different combinations of soil and vegetation types. These relationships were used to upscale recharge across northern Australia on a 0.05° grid using maps of soil, vegetation and annual average rainfall as co-variates. A chloride mass balance requires measurements of chloride deposition and concentration of chloride in groundwater. A review of field studies over the last few decades has provided a relationship between chloride deposition and distance from the coast; this has enabled a raster layer to be developed of chloride deposition across northern Australia. The chloride concentrations in groundwater have been assessed from data collected by the WA, NT and Qld state agencies. The baseflow analysis was conducted on gauged data collected by the WA, NT and Qld state agencies using the Eckhardt (2005) filter and converted to a depth using the catchment area as determined using a digital elevation model.

At a point scale both estimates of recharge and the estimate of discharge showed a range of over three orders of magnitude, from less than 1 mm/yr to over 1000 mm/yr. As a gross generalisation, the relative magnitudes between the three methods were as expected from a conceptual point of view: the upscaling of the SVAT model had the greatest recharge; the chloride mass balance method gave less recharge than the upscaling of the SVAT model; and, the groundwater discharge was the lowest of the three estimates. The upscaling of the SVAT model is an estimate of gross recharge (water added to the saturated zone), the chloride mass balance is an estimate of net recharge (gross recharge – ET from GW) and the baseflow is groundwater discharge to surface water which should be less than recharge due to groundwater extraction and ET from the riparian zone. Each technique therefore provides complementary information to assist future groundwater resource planning in northern Australia.

Keywords: *recharge, discharge, chloride mass balance, baseflow separation, WAVES model*

1. INTRODUCTION

The long-term management of groundwater resources requires careful estimation of the key components of the groundwater balance, including recharge and discharge. Traditionally the setting of upper limits for groundwater allocations has been on the basis of average recharge, but recent acknowledgement that surface water and groundwater are linked has required that the impact of pumping upon groundwater discharge is considered when setting water allocations. It has long been argued (Bredehoeft, 2007; Theis, 1940) that the size of a groundwater resource is determined by the amount of captured discharge and induced recharge, rather than the rate of natural recharge. A determination of the amount of natural recharge and discharge is thus a useful step toward estimating the capture.

There are few methods available to estimate groundwater recharge and discharge over very large, data–poor areas. We have used three independent methods to estimate the recharge and discharge across $1.2*10^6$ km^2 of northern Australia. This area is largely undeveloped and so the estimates of recharge and discharge attempted here represent close to natural conditions.

2. METHODS

While the methods employed here are suited to large data poor areas it is important to understand that they are not estimating the same quantity and so cannot be directly compared. Gross recharge (R_g) is water that passes the root zone and crosses the plane of the water table, net recharge (R_n) is that proportion of groundwater recharge that is not subject to evapotranspiration and groundwater discharge is groundwater that leaves the saturated zone as baseflow (B) to streams or evapotranspiration. Gross recharge has been estimated by upscaling the results of a 1-D SVAT model, which assumes that water that flows through the soil column becomes recharge. The model assumes a 4 m soil column with a free draining lower boundary condition. Net recharge is estimated using a steady state chloride mass balance. Groundwater discharge has been estimated using a digital filter on stream gauging data; thus only estimating the baseflow component of groundwater discharge. A relative comparison of each method will be presented at the scale of the 13 reporting regions (~100,000 km^2) defined for the *Northern Australia Sustainable Yields Project* (CSIRO, 2009).

2.1. Gross Recharge

The 1-D SVAT Model WAVES (Zhang and Dawes, 1998) has been used to model unsaturated zone water transport at a series of control points that encompass the rainfall gradient across the study area. The WAVES model parameters were derived from national datasets of climate (SILO) (Figure 1a) (Jeffrey et al., 2001), soils (ASRIS) (Figure 1b) (McKenzie et al., 2005) and vegetation (IVC03) (Figure 1c) (BRS, 2003). At each of 23 control points every combination of 12 soil types and 3 vegetation types encountered across northern Australia has been modelled to generate regression equations between average annual rainfall and average annual recharge. These regression equations have been combined with rasters of annual rainfall and soil and vegetation type to enable gross recharge to be estimated on a 0.05° grid. Gross recharge for a given reporting region could then be aggregated from the raster.

2.2. Net Recharge

The steady state chloride mass balance (CMB) approach is based upon the fact that evapotranspiration removes water but not chloride and hence chloride is concentrated in the groundwater. Knowing the chloride deposition and concentration of chloride in groundwater enables an estimate of the net recharge to be made. Eriksson (1985) showed that it is the arithmetic mean of the deposition (D) and the harmonic mean of the groundwater chloride concentrations (C_{gw}) that are used in the CMB:

$$\overline{R}_n = \overline{D}\,\overline{\left(1/C_{gw}\right)} \tag{1}$$

Literature values of chloride deposition across northern Australia were collated and a regression equation was fitted with chloride deposition versus distance from the coast. The double exponential form of the regression equation has previously been used by Keywood et al. (1997). The use of the regression equation enabled chloride deposition to be modelled on a 0.05° grid across northern Australia.

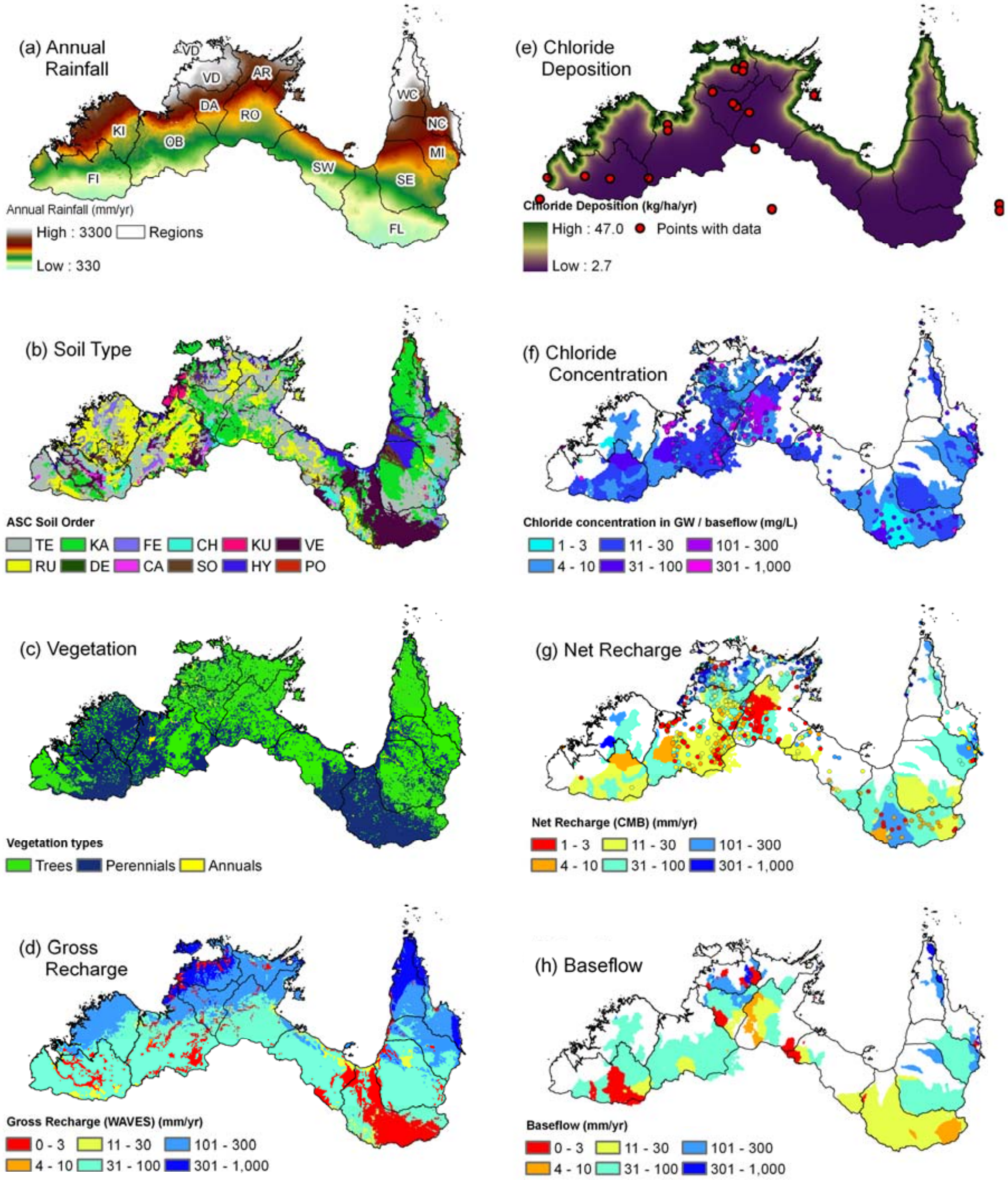

Figure 1. (a) Average annual rainfall (1930-2007) across northern Australia, also showing the reporting regions for the Northern Australia Sustainable Yields project (the abbreviations are defined in Figure 4) (b) Soil Types of northern Australia [TE – Tenosols, KA – Kandasols, FE – Ferrosols, CH – Chromosols, KU – Kurosols, VE – Vertosols, RU – Rudosols, DE – Dermosols, CA – Calcarosols, SO – Sodosols, HY – Hydrosols, PO – Podosols] (c) simplified vegetation types of northern Australia (d) Gross recharge as estimated from the upscaling of point modeling using WAVES (e) Chloride deposition across northern Australia and the locations of previous field measurements of chloride depositon (f) Chloride concentration in groundwater (points) and baseflow (patches) (g) Net recharge as determined by chloride mass balance in groundwater (points) and baseflow (patches) (h) Baseflow as determined using a digital filter of gauged streamflow.

The chloride concentration of groundwater was estimated from all measurements recorded in the state databases for bores drilled less than 20 m deep. In some areas there was very little data so the chloride concentration of streams during the dry season was also used. Using the stream concentrations of chloride assumes that the stream is entirely groundwater fed during the dry season. Where stream chloride concentrations have been used they are treated as a point estimate in the same way as the chloride measurements of groundwater.

2.3. Baseflow

A recursive digital filter was used to separate the baseflow from the total flow at all the gauging stations where chloride measurements were available across northern Australia. Although the most widely used filter in Australia is still the one proposed by Lynne and Hollick (1979), this has no physical basis and has been criticised for not being able to match tracer studies (Grayson et al., 1996). The form of the filter used for this study is as suggested by Eckhardt (2005):

$$b_k = \frac{(1 - BFI_{\max})\, a\, b_{k-1} + (1-a) BFI_{\max}\, y_k}{1 - a\, BFI_{\max}} \tag{2}$$

where b_k is baseflow at time k, y_k is total flow at time k, BFI_{max} and a are fitting parameters. The values used for the fitting parameters are parameters recommended by Eckhardt (2005) as appropriate for an ephemeral stream with a porous aquifer; BFI_{max} = 0.5, and a = 0.925. These parameters make this filter equivalent to the one proposed by Chapman and Maxwell (1996).

The baseflow was averaged over the time of gaugings to obtain an annual average; this was divided by the area of the gauged sub catchment to get the baseflow as a depth which can then be readily compared to the estimates of gross and net recharge. It was assumed that the effect of missing values in the gauging record would be minimal across the timeframe of investigation.

To aggregate results to a reporting region, an area averaged baseflow depth was used. In nested catchments, the area used is the area that is not measured by another gauge. In this way an area is only counted once no matter how many gauges are downstream of that point.

3. RESULTS

3.1. Gross Recharge

From the 828 (23*12*3) WAVES model runs, regression equations were developed relating annual average rainfall and annual average gross recharge for each combination of soil (kandasols and vertosols shown here) and vegetation type (annuals, perennials and trees). Gross recharge was found to be higher under annual vegetation than perennial vegetation and was also found to be higher under coarse textured soils than heavy clays (Figure 2). This is consistent with previous field and modelling studies.

These regression equations were used with rasters of average annual rainfall and soil and vegetation type to create a raster of gross recharge (Figure 1d). This raster of gross recharge generally follows the same pattern as the rainfall with high rainfall corresponding to high recharge. The exception to this is areas of Vertosol soil type where gross recharge is particularly low irrespective of rainfall.

3.2. Net Recharge

There were 21 locations with chloride deposition estimates collated from the literature over the past few decades; this is spatially variable and conspicuous by the complete lack of data from within the study region in Queensland (Figure 1e). There is a lot of scatter in the relationship between chloride deposition (D) and the distance from the coast (x) resulting in a wide confidence interval around the line of best fit (Figure 3). The regression equation fitted was:

$$D = 44.2 e^{-0.0288x} + 2.83 e^{-4.05*10^{-11} x} \tag{3}$$

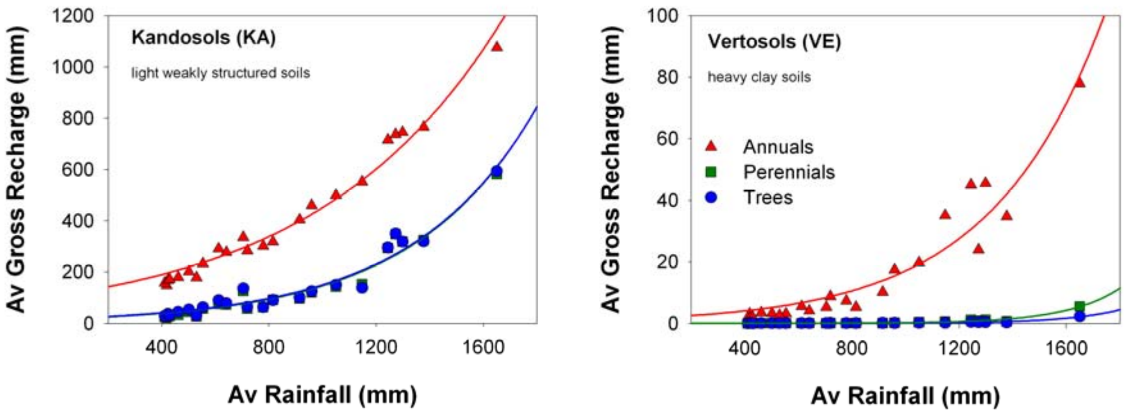

Figure 2. Relationship between average annual rainfall and annual average gross recharge for two different soil types and three vegetation types. The dots on the figure represent the output from the WAVES model and the lines are an exponential regression line fit through the WAVES outputs.

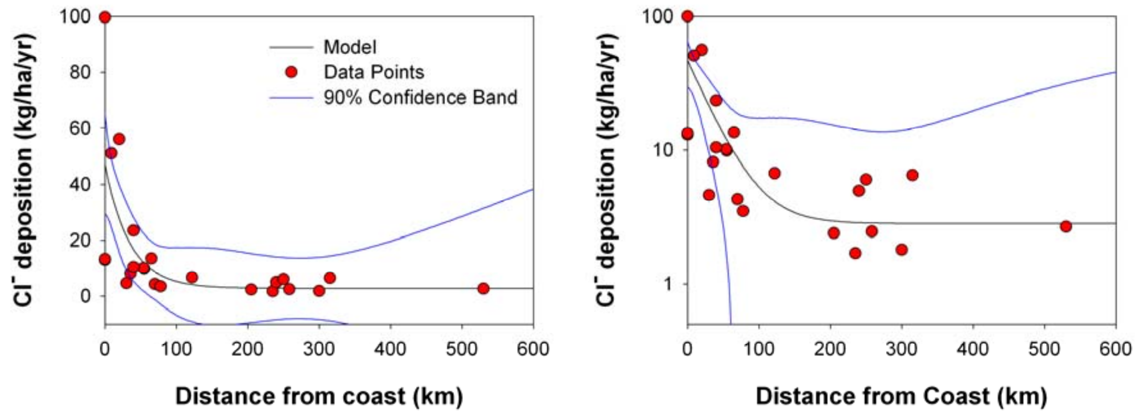

Figure 3. Relationship developed between chloride deposition and distance from the coast using a double exponential decay function. The left plot shows chloride deposition on a linear scale and the right plot shows chloride deposition on a logarithmic scale.

The amount of data available for the estimation of chloride in groundwater is not great. There were 2759 bores with data and this was supplemented with 210 surface water locations with estimates of dry season chloride. The most data poor area was the Kimberley (KI) with no estimates of chloride in groundwater and only 11 gauging stations with measurements of dry season chloride concentration in surface water. The most data rich area was Van Dieman (VD) which had 1527 bores with measurements of chloride in groundwater and 56 gauging stations with measurements of dry season chloride concentration in surface water.

The individual estimates of net recharge from a single bore or gauging station were quite variable (Figure 1g) ranging from 1 to >1000 mm/yr from the surface water estimates and from 0.1 to >1000 mm/yr from the groundwater estimates. The extreme values are recorded from locations with very little data and on occasion only a single estimate of chloride concentration. When all the observations from a reporting region are combined an average estimate of the net recharge is always less than the rainfall.

3.3. Baseflow

The results of the baseflow separation were also spatially variable (Figure 1h) with a highest value of 1700 mm and the lowest of <1 mm. As has been found in other studies (Petheram et al., 2008) the baseflow index increased with increasing catchment size. It is hard to distinguish whether this is due to increased groundwater discharge in the lower parts of a catchment or peakflow attenuation; the actual process is hard to discern.

3.4. Comparison between results

When the different methods are aggregated to a common reporting level they can be compared. Care needs to be taken as the three methods are not estimating the same quantity and the estimates used in the aggregation are not spatially consistent between methods (Figure 1). The working hypothesis was that gross recharge should be the highest and baseflow the lowest. However, this occurred in only 3 of the 13 reporting regions (LHS Figure 4). Generally the gross recharge estimates were greater than the net recharge estimates (9/13) and the baseflow estimates (12/13). The calculation of net recharge allowed error estimates to be calculated from the 90% confidence limits in the chloride deposition and the chloride concentration. These error estimates are very wide due to uncertainty in the chloride deposition estimates, and in 9 of the 13 reporting regions, the error bars on the net recharge encompass the estimates of gross recharge and baseflow.

A scale that can be directly compared is the estimated net recharge determined using the surface water (SW) chloride concentration during the dry season and the estimated baseflow when the two estimates are for the same gauging station (RHS Figure 4). The comparison shows that at a point scale the correlation between the two methods is generally consistent. Further, at the broad scale, spatial patterns of recharge and discharge are as expected, with the highest recharge and discharge in the highest rainfall areas of the Van Dieman, Western Cape and Northern Coral Sea and the lowest recharge and discharge estimated to be in the low rainfall areas of Flinders-Leichardt and South-West Gulf.

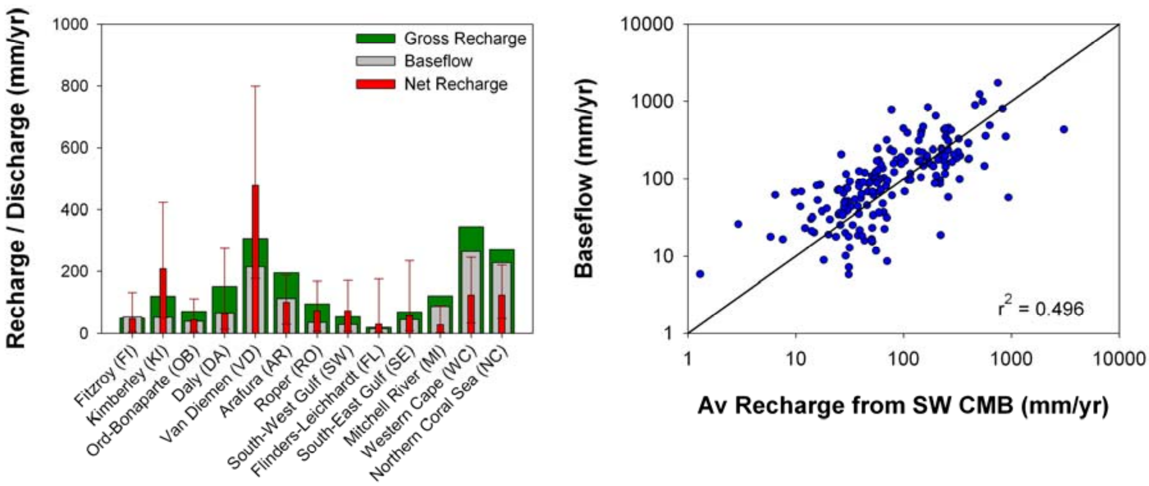

Figure 4. Comparison of methods. The left plot shows a comparison between the three methods at the scale of the reporting regions as defined by the Northern Australia Sustainable Yields Project. The right plot compares the baseflow and CMB at the catchment scale, the straight line represents a 1:1 relationship.

4. DISCUSSION AND CONCLUSIONS

Three methods were successfully used in estimating recharge or discharge across northern Australia. Each is reliant upon parameter sets which need high levels of estimation as they are not routinely measured in many areas. However, each method is particularly dependant on estimates of key data sets. Thus the gross recharge estimations are very dependant upon soil properties, particularly hydraulic conductivity; different soil types can produce recharge estimates that differ by orders of magnitude. Hence this approach is dependant upon the accuracy of soil mapping. Net recharge estimates are very sensitive to estimates of chloride deposition; the wide confidence intervals shown here demonstrate that the data availability is less than ideal to use this methodology across this area. Separating stream flow into quickflow and baseflow using digital filters assumes that the filters are capable of baseflow separation, there are many different filters that have been used in the past and most have very little justification in terms of representing physical processes. The literature values used for the filter require further validation for Northern Australia.

Despite the limitations of the estimates of recharge and discharge presented here, they demonstrate that national broadscale data sets can be used effectively in estimating recharge and discharge in relatively undeveloped data poor areas. This analysis can indicate where more detailed field based measurements need to be undertaken to reduce uncertainty if detailed water resource planning in stressed areas is to be achieved.

ACKNOWLEDGMENTS

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