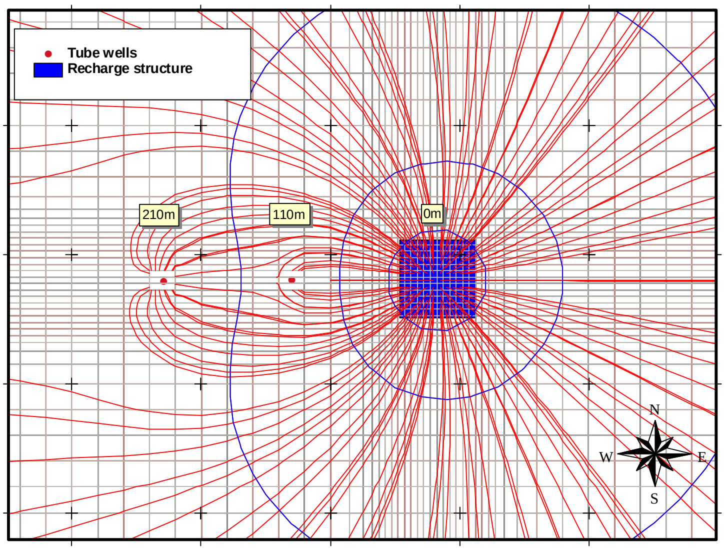
Numerical approaches for approximating technical effectiveness of artificial recharge structures

Groundwater Systems and Water Quality Programme

Commissioned Report CR/04/265N



BRITISH GEOLOGICAL SURVEY

GROUNDWATER SYSTEMS AND WATER QUALITY PROGRAMME
COMMISSIONED REPORT CR/04/265N

Numerical approaches for approximating technical effectiveness of artificial recharge structures

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Front cover

Pathlines of particles originating from a recharge structure, illustrating movement of recharge water in the aquifer.

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Summary

This report describes various numerical approaches to quantify technical effectiveness of low-technology artificial recharge structures as seen commonly in rural environment and communities in semi-arid developing countries. The described methodologies enable benefits of artificial recharge facilities, i.e. their ability to replenish the aquifer, to be approximated. Technical effectiveness of recharge facilities is thereby evaluated on three scales:

On a recharge basin scale, the rate of infiltration in relation to evaporation is established for different hydrogeological scenarios. This determines if the structure is fit for the purpose and can be investigated by measurements of water level declines in reservoirs during periods of no inflow and outflow except for recharge and evaporation loss. In a second step, the area of benefit, i.e. the zone of impact of the artificial recharge structure is studied, which is dependant on time scale and hydrogeological conditions at the site. This establishes the likely beneficiaries of the scheme. Thirdly, the hydraulic capacity, which is the accumulated infiltration over a long period that includes dry periods, is put into context with naturally occurring recharge in the area and the overall water demand in the local community surrounding the structure. This determines the overall significance of the scheme for the local rural community.

The work described was carried out as part of the DFID-funded project on "Augmentation of Groundwater by Artificial Recharge" (AGRAR).

1 Introduction

In recent years India has seen a substantial rise in abstraction to meet rising demand for domestic supplies and irrigation. Concerns are being raised about the sustainability of the resource and the livelihoods it supports given the current groundwater exploitation. One of several measures adopted in India to address problems of groundwater depletion is the promotion of the use of water harvesting structures to increase recharge. A range of facilities from traditional to sophisticated are employed. For a detailed description the reader is referred to (Gale et al., 2002). Considerable investment and effort are put to restore and maintain such facilities, however no systematic evaluation of their technical performance has been carried out. The benefits of such structures are often anecdotal and their overall performance is currently not established.

While the overall effectiveness of artificial recharge schemes is governed by a variety of factors such as climate, hydrogeology, source water availability and quality, operational and management issues and socio-economic considerations, this study is focusing on the technical aspects of the effectiveness of recharge facilities, i.e the ability of the structure to recharge the aquifer. Various numerical approaches are introduced to quantify technical effectiveness of low-technology recharge structures as seen commonly in rural environments and communities in semi-arid developing countries such as India.

The technical effectiveness of the recharge facilities is evaluated at three scales:

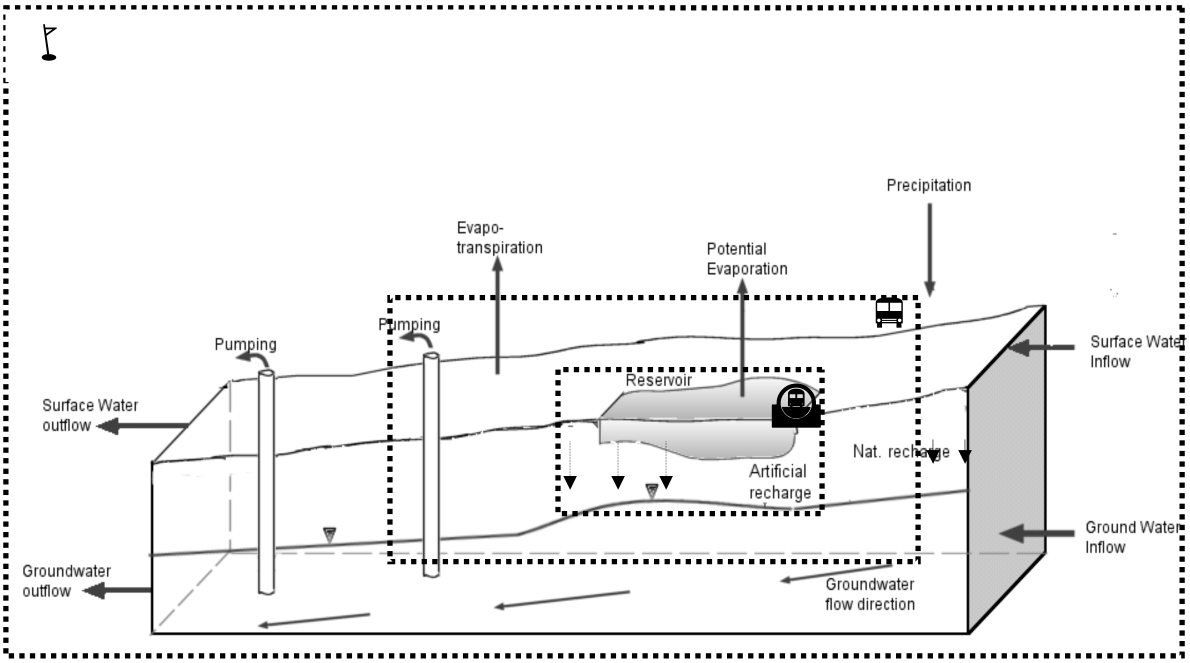


Figure 1.1 Technical effectiveness of artificial recharge structures is evaluated at three levels

Recharge basin scale

At the recharge basin scale, the decline in reservoir water levels over time is an indicator for the performance of a recharge structure. During periods of no inflow to and outflow from a reservoir, except groundwater recharge and evaporation loss, the decline in the reservoir water level is attributable to the sum of recharge and evaporation losses. The balance between these two losses determines, whether the structure is fit for the purpose, i.e. if water provides recharge rather than being lost to evaporation (section 2).

Impact of artificial recharge on aquifers

Besides establishing to what degree a recharge structure enhances recharge into the ground, the impact of this added recharge on the aquifer needs to be quantified. The area of benefit, i.e. the zone of raised water levels dependant on time, is estimated, establishing the likely beneficiaries of the scheme (section 3).

Impact of artificial recharge on groundwater availability at community level

To establish, if the added recharge significantly enhances the groundwater availability for a community served by a structure, the hydraulic capacity of the artificial recharge structure, which is the accumulated infiltration over a long period that includes dry periods, needs to be put into context with the water demand in the area. This determines the overall significance of the scheme for the local rural community (section 4).

This study introduces numerical approaches to quantify the effectiveness of recharge structures on all three scales described above. The study is generic in nature, evaluating impacts of artificial recharge for a range of aquifer settings and recharge quantities, which are chosen to be consistent with those occurring in the Indian case study areas under investigation. It is beyond the scope of this study to present the findings of local Indian case studies. For this, the reader is referred to Palanisami et al. (2004), Mudrakartha et al. (2004) and Kulkarni et al. (2004) and Gale et al. (2002, 2003).

The report structure is based on the three scales for which the effectiveness of artificial recharge structures is quantified, as outlined above. After the introduction in section 1, section 2 evaluates the effectiveness of recharge structures at the reservoir basin scale. Section 3 introduces numerical and analytical modelling to quantify the impact of recharge reservoirs on aquifers, while section 4 establishes the overall significance of the added recharge for the local community in terms of its share of naturally occurring recharge and abstraction volumes. An overall summary is provided in section 5. This is followed by two appendices showing numerical modelling results and the references.

2 Effectiveness of artificial recharge structures at the reservoir basin scale

The water balance for a reservoir can be simplified during periods of no precipitation and when surface inflow and outflow can be neglected. A further simplification can be made if losses due to leakage, abstraction etc can be neglected, and if the reservoir is under effluent conditions in relation to the aquifer, then the water balance can be summarized as:

Groundwater Recharge = Change of volume of water in the reservoir - Evaporation

Under such conditions, the balance between evaporation and groundwater recharge will determine the effectiveness of the artificial recharge scheme.

2.1 APPROXIMATING SHARE BETWEEN GROUNDWATER RECHARGE AND EVAPORATION LOSS FROM RESERVOIR STAGE DECLINES

To estimate the balance between evaporation and recharge losses from a reservoir in the Indian case study sites, the change in reservoir water level with time is monitored. For periods without direct abstraction and rainfall, this is translated into groundwater recharge rates after subtracting known or estimated open pan evaporation rates.

Figure 2.1 illustrates the relationship between the reservoir stage decline and recharge rates considering different evaporation rates. It is thereby assumed that the unsaturated zone is not limiting the rate of infiltration.

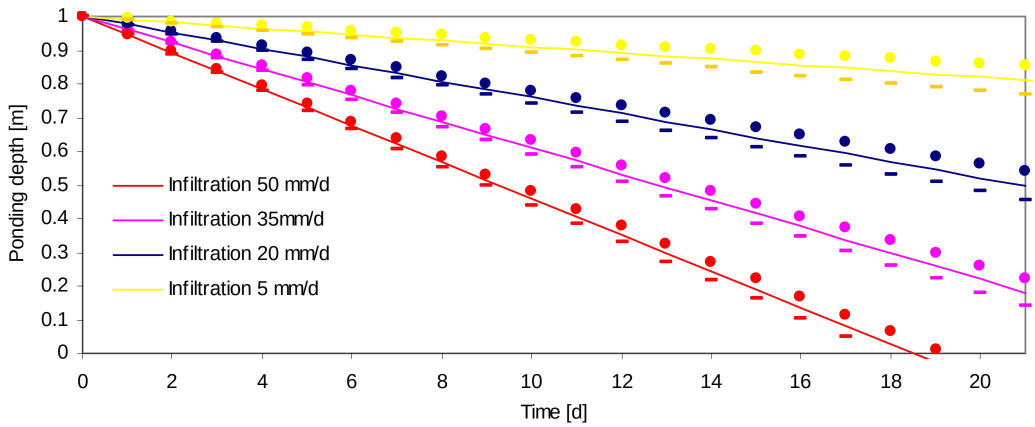


Figure 2.1 Decline in reservoir water level over time for various infiltration and evaporation rates (solid line: evaporation 4 mm/d, dotted line: evaporation 2 mm/d, dots: evaporation 6 mm/d).

Steady state conditions are assumed and the drop in water level shown in Figure 2.1 is linear. The steeper the line, the greater the recharge rate. With the initial ponding depth set to 1m, the reservoir is dry after 19 days for the fastest infiltration and lowest evaporation rate and after 91 days for the slowest infiltration and highest evaporation rate applied. This translates into 96% recharged and 4% lost to evaporation in the most favourable case and 45% recharged and 55% evaporated for the worst case scenario.

The rates shown in Figure 2.1 broadly cover the range of decline rates observed in Indian study sites. Rates are found to vary broadly for different reservoirs. Decline rates as low as 3.6 mm/d suggest some reservoirs to be 100% inefficient, acting basically as evaporation pans. Other reservoirs however show water level declines as high as 24 mm/d, suggesting considerable recharge. Figure 2.2 provides an example of water level changes in the Kodangipalayam watershed in Tamil Nadu (Palanisami et al., 2004), displaying a wide range of declines. However, it is beyond the scope of this report to detail and discuss the findings in the Indian study areas. These are described in detail in Gale et al. (2002, 2003), Palanisami et al. (2004), Mudrakartha et al. (2004) and Kulkarni et al. (2004).

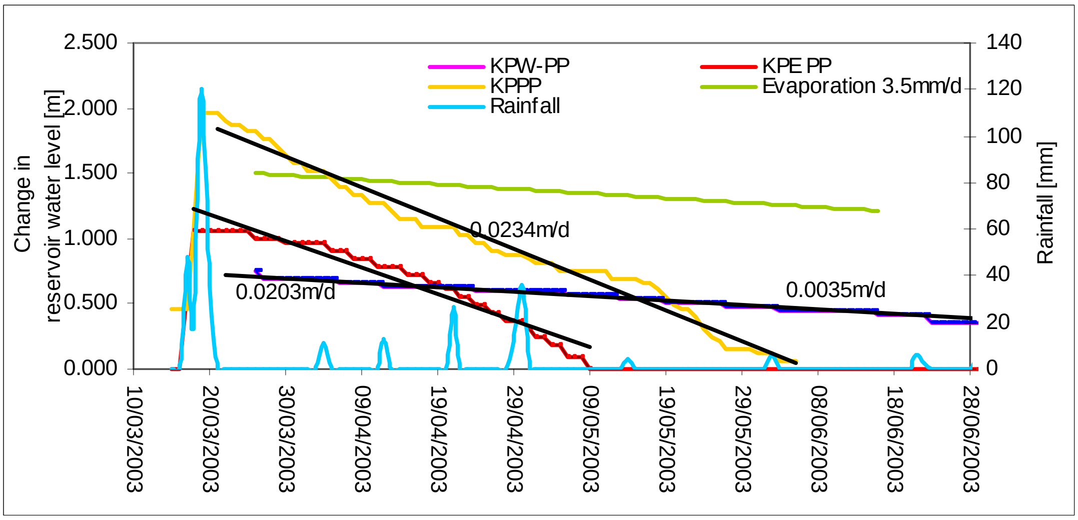


Figure 2.2 Examples of reservoir stage declines in the Kodangipalayam watershed in Tamil Nadu (Palanisami et al., 2004).

2.2 SHARE BETWEEN GROUNDWATER RECHARGE AND EVAPORATION LOSS OF RESERVOIRS IN RELATION TO GROUND PERMEABILITY

The balance between evaporation and groundwater recharge from a structure is controlled to a large degree by the permeability of the ground underlying the reservoir, which can be illustrated by describing the vertical one-dimensional water flow from the reservoir through the soil profile by Darcy's law:

$$q = K(\Theta)(dH / dL) \qquad \text{[Length/time]}$$

where q is the water flux [L/T], Θ the volumetric water content [dimensionless], $K(\Theta)$ the hydraulic conductivity [L/T], and dH/dL the hydraulic gradient with depth.

To simplify the above, we consider steady state conditions for the unsaturated zone. Since piezometric heads are then unchanging in time, the volumetric water content Θ is constant and the hydraulic conductivity will not change with time. The infiltration rate through the soil zone is then the product of the soil permeability times a constant hydraulic gradient.

Based on the above, the effect of the permeability of the subsurface on the amount of water being recharged as well as evaporated, can be represented by the following equations:

$$R_t = Hq/(E+q)$$

$$E_t = HE/(E+q)$$

R_t = Total recharge [mm]

E_t = Total evaporation loss [mm]

q = K(Θ) * dH/dL [mm/d]

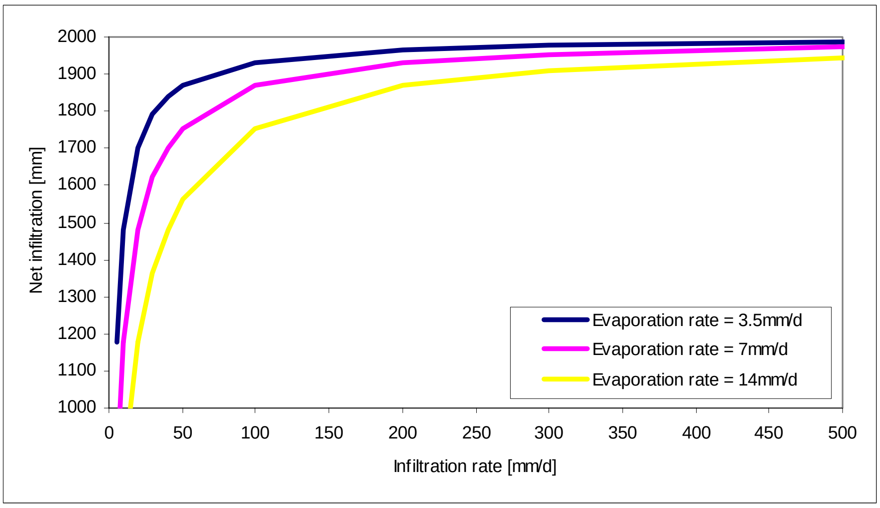
E = Open water evaporation rate [mm/d]

H = Initial height of the water column in the reservoir [mm]

Based on the equations given above, the balance between recharge and evaporation loss for various subsoil permeabilities is calculated (Table 2.1) and illustrated in Figure 2.3. Calculations are based on an initial depth of water in the reservoir, which is applied for recharge, of 2000 mm. The open water evaporation is assumed to be 3.5 mm/d, while a unit hydraulic gradient (dh/dz = 1) is assumed. This approach assumes a steady downward flux to the water table. Factors, which might affect the recharge rate, like moisture content in the unsaturated zone, decrease in ponding depth in the reservoir or rise in the groundwater table are not considered. This approach is therefore a fair approximation for reservoirs situated on thick unsaturated zone profiles, which permit a steady downward flux to the water table (Bouwer, 1989). It is less suitable in cases of shallow unsaturated zones, where e.g. a rising groundwater table or a decrease in reservoir stage during recharge periods could change the hydraulic gradient markedly. Both processes will lead to a gradual decrease in infiltration rates over time (see section 2.3).

Table 2.1 Effect of soil permeabilities on infiltration rates and net infiltration

Soil permeability K [m/d]	**0.02**	**0.04**	**0.4**	**0.8**
Total evaporation loss (Et) [mm]	298	161	17	9
Total recharge (Rt) [mm]	1702	1839	1983	1991
Water in reservoir [days]	100	50	5	2.5
% of water recharged	85.1	92	99.2	99.6



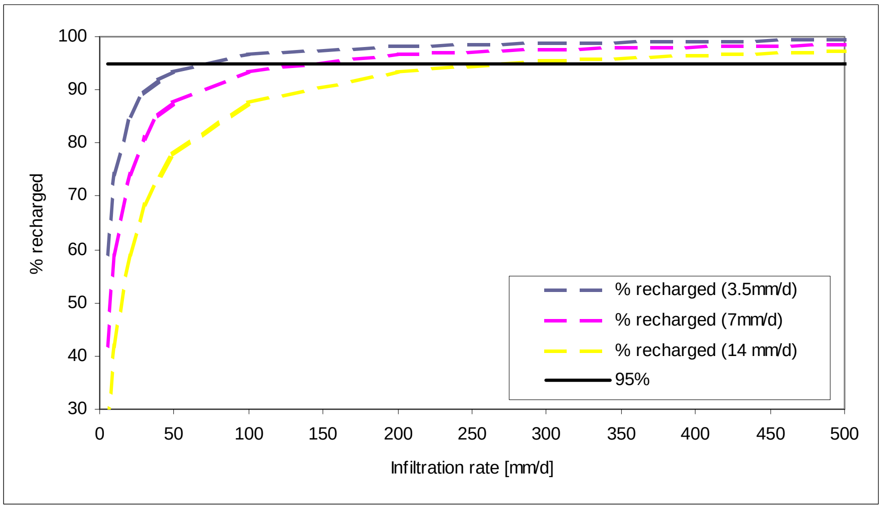


Figure 2.3 Relationship between a) net infiltration and soil permeability and b) % recharged and soil permeability for three open water evaporation rates. The ponding depth in the reservoir is 2000 mm.

Table 2.1 and Figure 2.3 illustrate that for soil permeabilities above 300 mm/d the net infiltration is not significantly affected by the infiltration rate: water recharges rapidly and evaporation only accounts for a small percentage of the total reservoir water loss. Lower infiltration rates effect the total net recharge considerably with large percentages of reservoir water being lost to evaporation.

2.3 FACTORS AFFECTING RESERVOIR STAGE DECLINES

Not always are stage declines linear as indicated in Figure 2.1. Various factors can influence stage declines over time and need to be considered when interpreting observed infiltration rates. Some, but not all, of these factors are listed below, followed by a brief outline of their impact on water level decline rates:

a) Change in hydraulic gradient

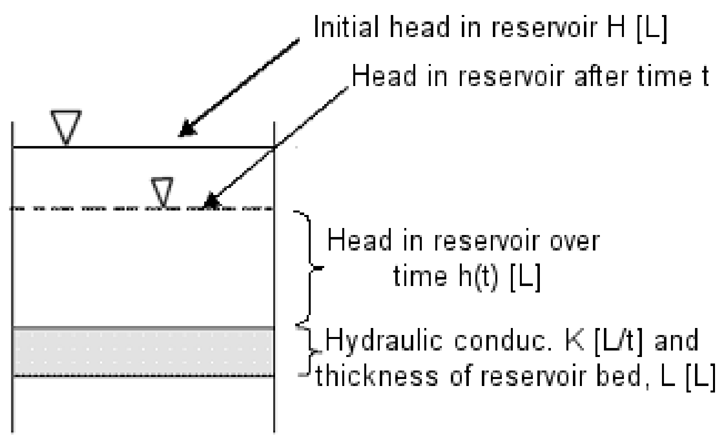
b) Change of reservoir bed thickness and/or permeability over time (e.g. through clogging, scraping)

c) Reservoir shape

A) CHANGE IN HYDRAULIC GRADIENT

For deep unsaturated zone profiles vertical flow is mainly governed by the soil/aquifer permeability. The infiltration approaches a finite value, which is the result of the system only being able to transmit a specific volume of water (Bouwer, 1989). If however a shallow unsaturated zone is considered, the measured infiltration rates in a reservoir are not directly related to the hydraulic conductivity of the ground. Vertical flow, governed by Darcy's Law, is the result of the permeability and thickness of the reservoir bed material and the head difference between reservoir and aquifer. Thus, a low infiltration rate can be the result of low ground permeability or the consequence of a low hydraulic gradient. Consequently, a rise in groundwater table during recharge events or a drop in reservoir water levels decreases the hydraulic gradient and subsequently the infiltration rate. As a result, rates of reservoir stage decline reduce over time (Figure 2.5).

The balance between recharge and evaporation loss from a reservoir is calculated under such circumstances on the basis of Darcy's law, taking the change of the hydraulic head with time (dh/dt) into account (Figure 2.4):



With $\frac{dh}{dt} = -E - \frac{Kh}{L}$ and $q = \frac{HK}{L}$ we obtain $\frac{dh}{dt} = -E - \frac{hq}{H}$. To determine the time it takes for the water table to fall between two points, say initial water table height H and height h, we integrate so that

$$\int_H^h \frac{dh'}{E + h'q/H} = -\int_0^t dt' ;$$

so

$$\frac{H}{q} \ln\left(\frac{E + hq/H}{E + q}\right) = -t .$$

Figure 2.4 Schematic diagram of changing reservoir level with time.

The time for the reservoir to empty, i.e. h = 0 can then be calculated as follows:

$$t_0 = \frac{H}{q} \ln\left(\frac{E + q}{E}\right)$$

Evaporation loss and recharge are given by:

$$Et = Et_o = \frac{EH}{q} \ln\left(\frac{E + q}{E}\right)$$

$$Rt = H - Et$$

Table 2.2 lists recharge and evaporation loss for various subsoils, based on the equations given above, assuming a reservoir bed thickness L of L = 1m, so that $Q \equiv K$, an initial depth of water in the reservoir of 2000 mm and an open water evaporation rate of 3.5 mm/d.

Table 2.2 Effect of soil permeabilities on infiltration rates and net infiltration if the change in reservoir stage during recharge events is considered

Soil permeability K [m/d]	**0.02**	**0.04**	**0.4**	**0.8**
Total evaporation loss (Et) [mm]	666	441	83	48
Total recharge (Rt) [mm]	1333	1559	1917	1952
Water in reservoir [days]	190	126	24	14
% of water recharged	67	78	96	98

A comparison with the model of a constant water flux to the water table introduced in section 3.1 (Table 2.1), it can be seen, that the declining hydraulic gradient over time leads to higher evaporation losses and lower recharge rates as water is retained in the structure for longer.

B) CHANGE OF RESERVOIR BED THICKNESS AND/OR PERMEABILITY OVER TIME (E.G. THROUGH CLOGGING, SCRAPING)

High loads of suspended solids in recharge water will increase the thickness of the filter cake at the bottom of the reservoir, thereby lowering infiltration rates. The impact is more significant when the total suspended solids concentration in the water is higher and recharge rates are greater. More important however, is the often accompanying decrease in reservoir bed permeability, due to the accumulation of silt, clay or other fine material or the growth of algae. The effect is a steady slowing of infiltration over time (Figure 2.5).

C) RESERVOIR SHAPES

Irregular reservoir walls can decrease or increase stage decline rate. If a steady-state downward flux of water is observed, the shape of the reservoir will determine the corresponding drop in the water level. Reservoirs with vertical walls lose water at a steady rate. A decrease in reservoir diameter however can result in increasing decline rates and vice versa (Figure 2.5).

In conclusion, reservoir stage declines serve as a good indicator for the reservoirs efficiency in recharging the aquifer. Generally, the faster the water level declines, the less water is lost to evaporation and the more efficient the reservoir is in recharging the aquifer. A summary of decline rates over time and their causes is shown in Figure 2.5.

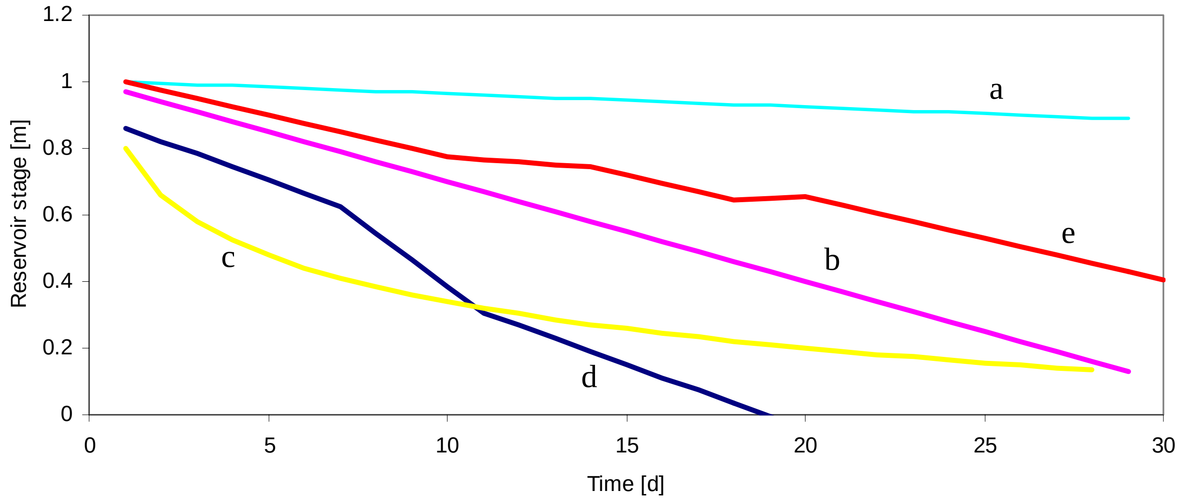


Figure 2.5 Classes of water level declines with time

a) Loss of water is due to evaporation.

b) Loss of water due to recharge >> loss due to evaporation. The steeper the decline, the grater the infiltration rate, the more effective the structure

c) Infiltration rate declines with time. This could be due to clogging or the subsurface becomes saturated and the hydraulic gradient decreases. If the unsaturated zone is thin below the basin the decreasing rate could also be the result of the decline in ponding depth in the recharge basin.

d) Variations in infiltration rate can be due to irregular basin shapes. Other causes might be direct abstraction and seepage through the dam wall.

e) The infiltration slows down for several days to then return to original rate. Caused by rainfall events.

3 Effectiveness of artificial recharge structures at the aquifer scale

In order to quantify the effect of the added recharge from small scale artificial recharge structures on aquifers of different properties, numerical modelling was undertaken.

The modelling exercise addresses the following aspects:

- Expected water level rise following recharge events under various hydrogeological settings.
- Impact zone of a recharge structure, i.e the area in which a rise in water level is experienced.
- Time scales over which water levels are raised, i.e time it takes for a groundwater mound to dissipate.
- The ability of tube wells to recover recharge water depending on aquifer properties and well position and depths.

The numerical modelling was undertaken using an analytical solution and a numerical model. Both approaches were used to model the same recharge and aquifer scenarios. However, the aim of using an analytical model was to provide a tool for impact assessment of artificial recharge structures for users not familiar with numerical modelling codes, such as MODFLOW (McDonald and Harbaugh, 1988). It allows users to investigate homogeneous aquifer systems and their responses to recharge using Excel spreadsheets. The model is simple in its set-up and can produce outputs in the form of graphs and tables in Excel (see Section 3.1). The numerical model was set up using the modelling code MODFLOW. It was used to verify the analytical code by simulating responses of homogenous aquifers to recharge events and comparing both model results. Additionally, it was used to simulate the impact of artificial recharge on non-homogenous aquifers and on abstraction rates in tube wells (see Section 3.2).

3.1 ANALYTICAL SOLUTION

To facilitate the estimation of effects of radially-symmetric patterns of pumping from a homogeneous aquifer, an analytical solution was developed by John Barker (Macdonald et al. 1998). This solution forms the basis for an Excel spreadsheet model used within this study to investigate the impacts of recharge to a homogenous aquifer, determining water level rises and volumes, respectively. The model assumes an isotropic, homogenous aquifer, with a recharge structure of radius R1 situated in the centre. A schematic diagram of this set-up is shown in Figure 3.1.

Recharge is distributed uniformly within the recharge structure at rates specified in $m^3/d/m^2$. The recharge rate is held constant over specified time periods. The model then calculates water levels in the aquifer and volume balances. Water levels are calculated at a given distance from the centre of a recharge structure. The calculated volume is the net gain of volume over the area out from the recharge structure to a specified radius, over a given time period. The aquifer can be treated as infinitive or a no-flow boundary can be defined at a radius equivalent to the extent of the aquifer. Details on the use of the spreadsheet are provided in Appendix 2.

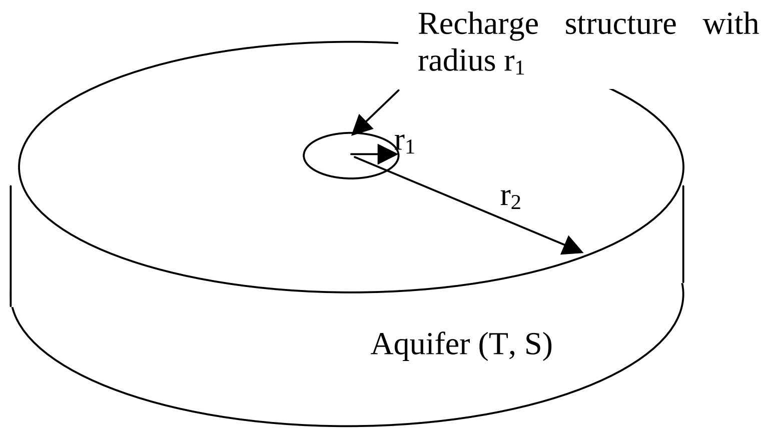


Figure 3.1 Schematic diagram of the analytical model set up. r_1 = radius of recharge structure, r_2 = radius of aquifer.

3.2 NUMERICAL MODEL

The numerical model developed to simulate the impact of recharge reservoirs under different hydrogeological scenarios is shown in Figure 3.3. It was constructed using the groundwater modelling code MODFLOW (McDonald and Harbaugh, 1988). The 2-D areal model is 1160 m square in size. The cell size increases from 5 metres in the centre of the model to 20 metres at its boundaries. It is bounded by general head boundaries with the same groundwater head all-round; no underlying regional hydraulic gradient is applied. A recharge reservoir of 55 m by 55 m is located at the centre of the grid and recharges at a rate of 48 mm/day for 30.4 days (1 month). The size of the structure and its recharge rate have been chosen to be within the range observed typically in Indian case studies. The model simulates radial flow outwards from the recharge structure similarly to the analytical model described in section 3.1. The transmissivity and storativity of the aquifer is varied in the model to cover a range of hydrogeologically plausible aquifer settings (Table 3.1).

The model is used to simulate a homogeneous intergranular aquifer and an aquifer that contains preferential flowpaths. The preferential flowpaths are simulated by specifying zones of increased or decreased permeability.

Abstraction from open tube wells has been included in some scenarios. These are specified to abstract at the maximum rate the aquifer properties permit. This is achieved by maintaining the water level at the base of the well by using a “drain” cell in the numerical model. The water level, above which drainage can occur, is specified to be the bottom of the tube wells with wells being “dry” if no recharge occurs. If recharge takes place, the total inflow to the tube well, i.e. the abstraction rate, is a function of head in the aquifer and the elevation of the bottom of the tube well, according to (eq.2):

$$Q = \begin{cases} 0 & H_{aq} \le H_{drain} \\ C\left(H_{aq} - H_{drain}\right) & H_{aq} > H_{drain} \end{cases}$$

With Q = flow into the tube well [L^3/T]
C = Conductance of the interface between tube well and aquifer [L^2/T]
H_{aq} = Head in the aquifer adjacent to the tube well [L]
H_{drain} Head in the drain (set to bottom of tube well) [L]

The conductance of the interface, separating the aquifer from the tube well, has been set high, which allows the drainage cell to act like a constant head cell for $H_{aq}>H_{drain}$. Consequently, there are no losses associated with the tube well and flow rates are governed solely by the aquifer's properties.

This approach enables the model to calculate the proportion the well is able to abstract in relation to the total volume recharged for different hydrogeological settings as well as different well locations. The schematic diagram in Figure 3.2 illustrates the inclusion of tube wells in the model. It has to be noted, that the approach is likely to overestimate flows to wells, as well losses and the development of a seepage face are not considered, which can lower flow rates.

Particle tracking is performed to plot the pathlines of particles originating from the recharge structure while recording the time of travel. Particles are placed on the water table over the full areal extent of the recharge structure. The spacing of the particles was chosen so that each particle represented the same volumetric recharge rate, i.e 1.1675 m^3/d of recharge.

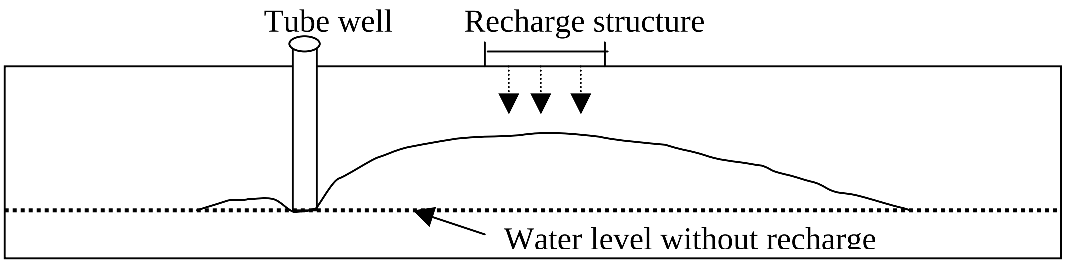


Figure 3.2 Schematic diagram of the inclusion of tube wells into the numerical model.

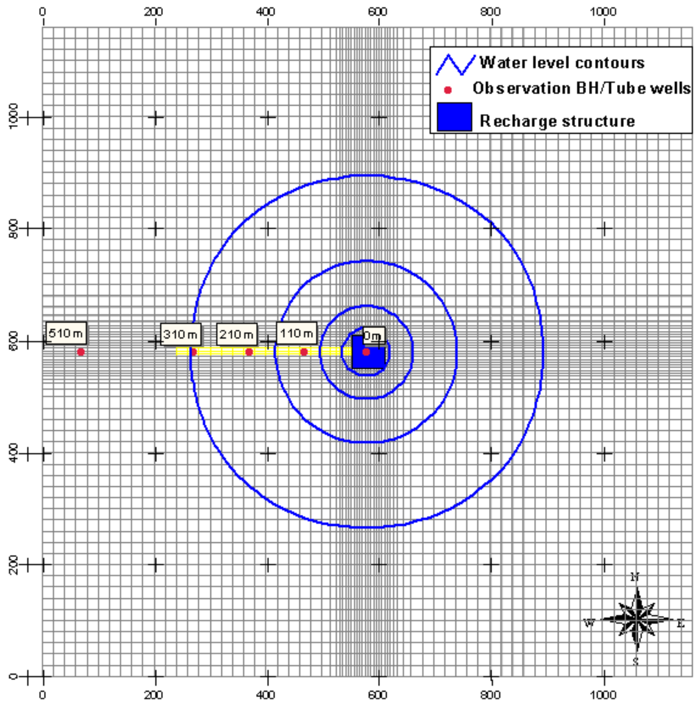


Figure 3.3 Schematic diagram of the set-up of the numerical MODFLOW model.

3.2.1 Simulations

In total, 28 transient simulations were run in which different transmissivities and storativities were applied to the aquifer. These are summarised in Table 3.1.

Table 3.1 Summary of scenarios simulated using the analytical and numerical model respectively

Scenario	Well	T	Spec. Yield	Comments
Sc1	-	300	0.1	Homogenous aquifer
Sc2	-	1500	0.1	Homogenous aquifer
Sc3	-	30	0.1	Homogenous aquifer
Sc4	-	15	0.1	Homogenous aquifer
Sc3frac	-	30	0.1	E-W zone of high permeability K: 50 m/d
Sc4frac	-	15	0.1	E-W zone of high permeability K: 50 m/d
Sc5	-	1500	0.2	Homogenous aquifer
Sc6	-	300	0.2	Homogenous aquifer
Sc7	-	300	0.05	Homogenous aquifer
Sc8	-	1500	0.05	Homogenous aquifer
TW_Sc1	1: 110 m	300	0.1	Homogenous aquifer
TW_Sc2	1: 110 m	1500	0.1	Homogenous aquifer
TW_Sc3	1: 110 m	30	0.1	Homogenous aquifer
TW_Sc4	1: 110 m	15	0.1	Homogenous aquifer
TW_Sc3frac	1: 110 m	30	0.1	E-W zone of high permeability K: 50 m/d
TW_Sc4frac	1: 110 m	15	0.1	E-W zone of high permeability K: 50 m/d
TW_Sc5	1: 110 m	1500	0.2	Homogenous aquifer
TW_Sc6	1: 110 m	300	0.2	Homogenous aquifer
TW_Sc7	1: 110 m	300	0.05	Homogenous aquifer
TW_Sc8	1: 110 m	1500	0.05	Homogenous aquifer
TW_Sc9frac	1: 110 m	1500	0.05	E-W zone of low permeability K: 1 m/d
TW_Sc10	3: all at 110 m	300	0.1	Homogenous aquifer
TW_Sc11	1: 210 m	300	0.1	Homogenous aquifer
TW_Sc12	1: 310 m	300	0.1	Homogenous aquifer
TW_Sc13	1: 510 m	300	0.1	Homogenous aquifer
TW_Sc14	2: 110 m and 210 m	300	0.1	Homogenous aquifer
TW_Sc15	3: all at 110 m, one twice the depths as others	300	0.1	Homogenous aquifer
TW_Sc16	2: 110 m and 210 m (twice the depth)	300	0.1	Homogenous aquifer

3.2.2 Model output

Both the analytical and numerical models output the water levels over time in the aquifer. These are plotted against time and against radial distance from the recharge structure.

The numerical model also calculates the volume of water removed from the aquifer through the tube wells, i.e. through the drainage cells, over time. These are compared to the total volume recharged.

Particle tracking is used to plot the pathline of particles originating from the recharge structure, while their travel time is also calculated. Particle tracking is performed running the model under steady-state conditions. While the travel times of particles are not discussed further in this modelling study, the graphs in Appendix 1 give some indication of time of travel, as all tracks have been plotted over a 50year period. The times calculated by the model are travel times under radial flow conditions outward from the recharge structure, with the recharge mound and abstraction being the only driving force for water movement in the aquifer. They reflect groundwater movement caused by the build up in water levels and need to be superimposed on any regional groundwater gradient present in the aquifer in order to obtain actual travel times.

Where the figures include results obtained by both, the analytical and numerical models, they are distinguished by an “A” (Analytical) or “M” (Modflow), respectively which are added to the scenario number. Scenarios involving heterogeneous aquifers or abstraction from tube wells have been undertaken with the numerical model only.

3.2.3 Results

TIME DEPENDENT WATER LEVEL CHANGES FOLLOWING RECHARGE EVENTS UNDER VARIOUS HYDROGEOLOGICAL SETTINGS

Homogenous aquifer

Water level rise in response to a one month recharge event (30.4 days) in a homogeneous aquifer have been modelled using four different transmissivities ranging over two orders of magnitude, from 15 m^2/d to 1500 m^2/d (Scenario Sc1 to Sc8). The effective porosity varies between 0.05 and 0.2. Figure 3.5 and Figure 3.6 show the model results for the analytical and MODFLOW model runs.

The water level in the aquifer rises to its maximum underneath the recharge structure at 30.4 days, when recharge ceases (Figure 3.6). The maximum is thereby dependent on the permeability of the ground, with highest water levels being achieved for the lowest conductivities and smallest effective porosities. The maximum water level built-up does not exceed 2.6 m underneath the recharge structure for any of the modelled scenarios. This decreases to maxima of below 0.4 m for all scenarios at a distance of 110 metres from the centre of the recharge structure. For high permeable aquifers (scenario Sc2) the maximum height of the recharge mound remains in the order of a few centimetres.

The recharge mound subsides quickly underneath the recharge structure by spreading radially outwards to occupy an ever increasing area of the aquifer (Figure 3.5). Subsequently, water levels fall sharply in the vicinity of the recharge structure over time but increase radially outwards in the aquifer. This increase however is small in all modelled scenarios, due to the recharge volume being small compared to the volume of the aquifer the water occupies over time. Maximum water level rises outside the immediate area of the recharge structure remain in the order of centimetres for all modelled scenarios.

The spreading of the recharge mound outwards from the recharge structure is shown in Figure 3.4 for scenarios Sc1 to Sc8, based on:

$$r = \sqrt{4Tt \ / \ S} \qquad (3)$$

with r = position of maximum in rate of water level increase [L]
T = transmissivity [L^2/T]
S = storativity
T = time [T]

Equation 3 describes approximately the propagation of the surge peak in water level change, created by the recharge event through the aquifer outwards from the recharge structure. The equation is derived from Theis' well function, for which an inflection point occurs at u = 1, that is , $r = \sqrt{4Tt \ / \ S}$ which gives the position of where the rate of water level increase is at a maximum for a given time.

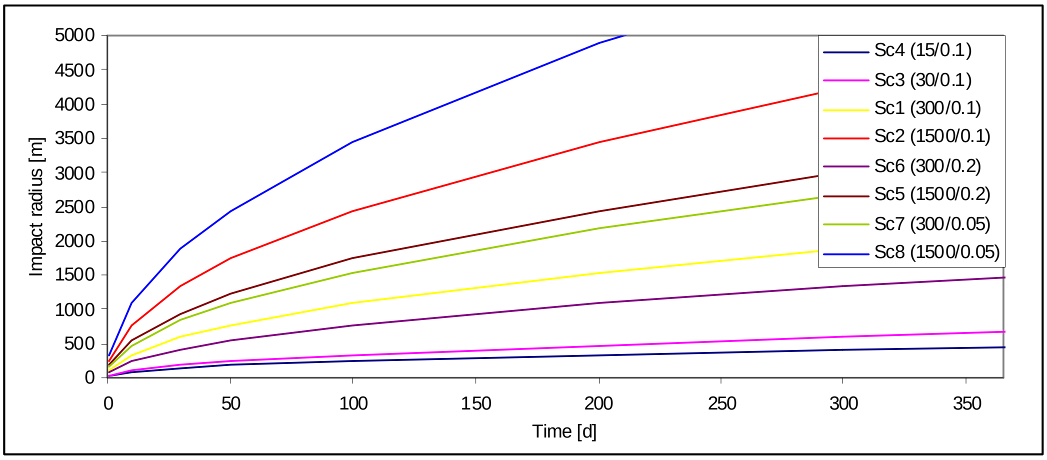


Figure 3.4 Propagation of water level change maxima, created by the recharge event at time t=0, with time and distance.

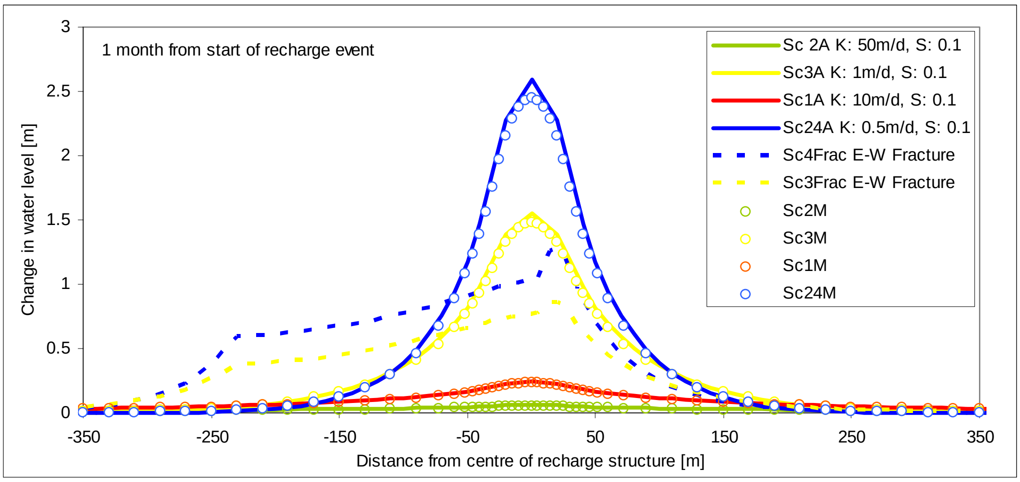
Figure 3.4 shows that the speed at which the maximum in the rate of water level change propagates through the aquifer is dependent on the aquifer properties. In aquifers of low diffusivity (T/S) a surge in water level change induced by a recharge event propagates at a slow pace through the aquifer compared to aquifers of high diffusivity.

While Equation (3) gives an indication of the impact zone of the recharge structure with time, it does not give any indication of the scale of impact, which can be minimal as shown earlier.

After the surge in water level change occurs, the decline in water level is rapid for permeable aquifers and prolonged if low transmissivities are considered (Figure 3.6). In a borehole at 110 metres distance from the recharge structure, the decline to half the peak level occurs in a matter of days under permeable conditions, i.e. 4 days in Sc2 and 9 days in Sc1. Under lower permeabilities, this drop in water level to half its maximum only occurs after 44 days (Sc3) and 71 days (Sc4) respectively.

Inhomogeneous aquifers

To establish the effect of heterogeneity on water levels, a high permeable zone (K: 50 m/d) was added to scenario Sc3 and Sc4, which could reflect e.g. a fractured zone or a high permeable weathered zone (Sc3frac, Sc4frac). The 15 m wide zone extends from the centre of the recharge structure 230 metres to the west. Its effect is to channel recharge water instead of spreading it evenly over a large aquifer volume in the case of the previously discussed homogeneous radial flow scenarios (Figure 3.9). The result, shown in Figure 3.5 and Figure 3.6, is an increase in water levels within this zone to several times the height observed under radial flow conditions in a homogenous aquifer, with elevated levels sustained over longer periods. For a tube well located at 110 m distance to the recharge structure in such a zone, this results in a maximum water level of about twice the height compared to the maximum under homogeneous conditions (Sc4frac). The effect increases with increasing K ratios between aquifer and permeable zone. The above illustrates the general effect of stronger impacts of the added recharge the smaller the receiving aquifer body; i.e the smaller the aquifer being recharged, the larger the effect.



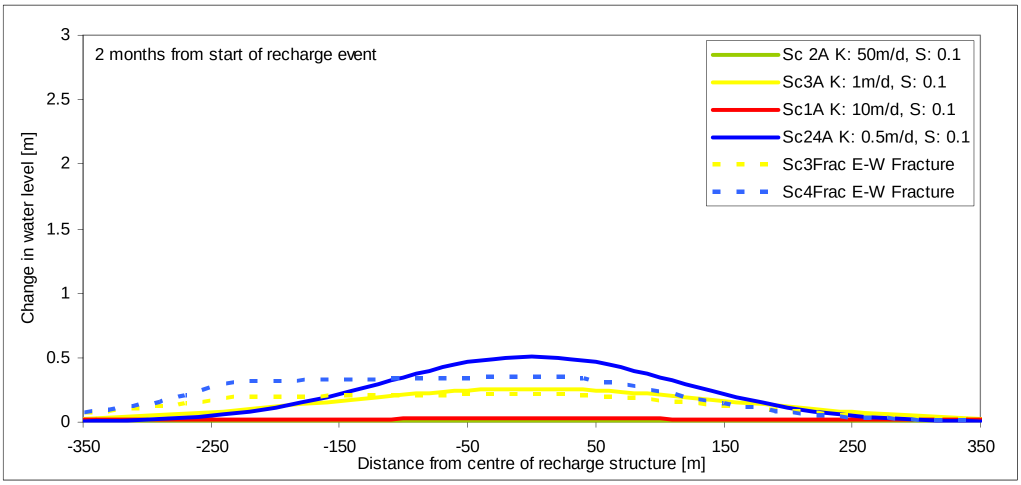
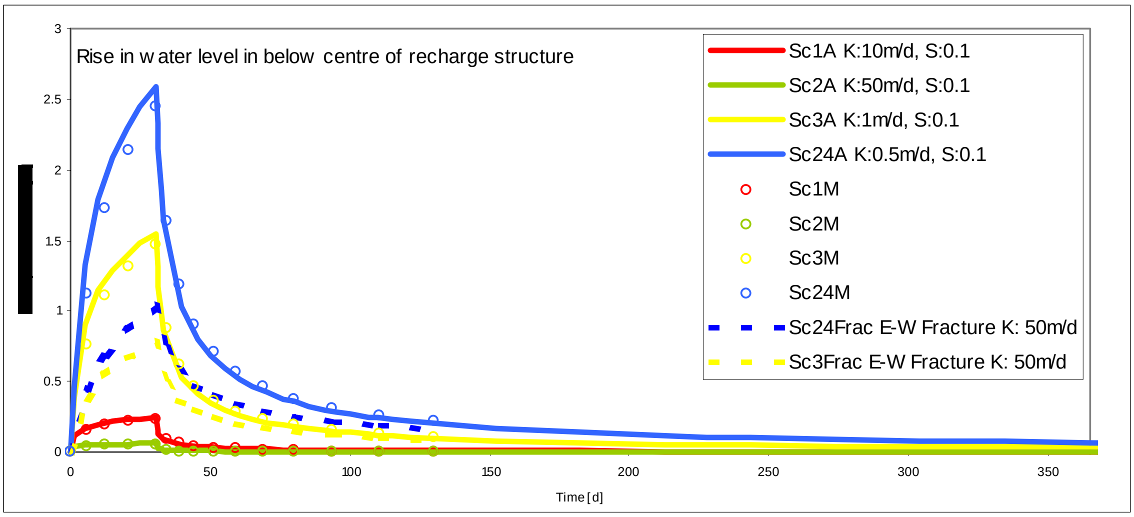


Figure 3.5 Change in water level due to a one month recharge event with distance from the centre of the recharge structure. Levels are shown for one month and two month after the start of the recharge event (see Table 3.1 for description of scenarios).



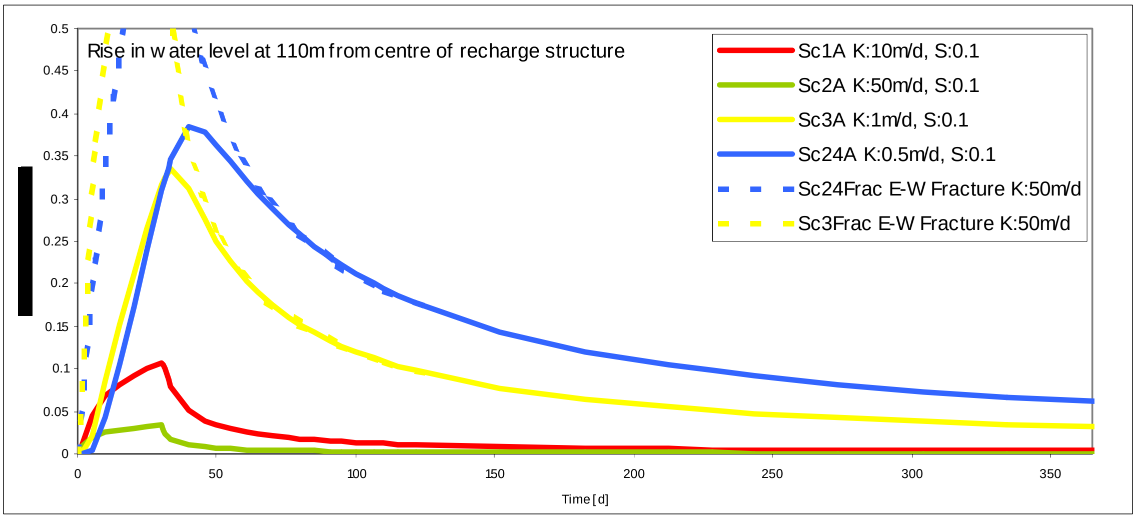


Figure 3.6 Change in water level due to a one month recharge event with time. Levels are shown at 0 m and 110 m distances from the centre of the recharge structure.

ABILITY OF TUBE WELLS TO RECOVER RECHARGE WATER DEPENDING ON AQUIFER PROPERTIES

To measure the effect of recharge events on abstraction volumes, a tube well 110 m from the centre of the recharge structure was added to the model (scenario TW_Sc1 to TW_Sc9frac). Maximum abstraction volumes are calculated by the model and are used to establish the proportion of water a tube well is able to abstract over time in relation to the total volume recharged. Results are compared for different aquifer properties.

The simulation results are shown in Figure 3.7 and Figure 3.12. These show the volume of water abstracted from a tube well 110 m from the centre of the recharge structure over time, cumulative volume abstracted and total volume abstracted as a proportion of total recharge.

The model results demonstrate that in the case of a homogenous aquifer, the tube well is able to capture around 33% of the total recharge. The total abstraction volume is nearly independent of aquifer properties (Figure 3.12), however, they determine the abstraction rate over time. Lower permeabilities and storativities will restrict the abstraction rate due to the fall in well water level as a cone of depression develops around the tube well. These lower rates however, can be sustained over a longer period. Scenario TW_Sc4, which represents a low permeability aquifer, calculates that the tube well is still able to abstract water 100 days after the recharge event at a rate of 2.3 m^3/d. Highly permeable aquifers permit high abstraction rates which are sustained over short durations. In scenario TW_Sc2 water levels fall rapidly and the tube well is dry only 14 days after the end of the recharge event, i.e the water level has fallen below the bottom of the well.

The intake of recharge water is substantially increased when tube wells are located in discreet zones of higher permeability (scenario Sc3frac and Sc4frac). Through channelling recharge water, these allow the tube well located within the zone to abstract 81% of the total amount recharged, compared to the 33% achieved under homogenous conditions (Figure 3.12). Besides abstraction rates being elevated, these can also be sustained over longer periods. In both scenarios the tube well is still operating at a rate of 2.3 m^3/d after 80 days after the recharge event (Figure 3.7). The opposite is observed if wells are located in zones of lower conductivity compared to the surrounding aquifer. Changing the permeability of the E-W zone of scenario Sc3frac from 50 m/d to 1 m/d results in a decrease in total abstraction from 81% to 3% of total recharge (Sc9frac).

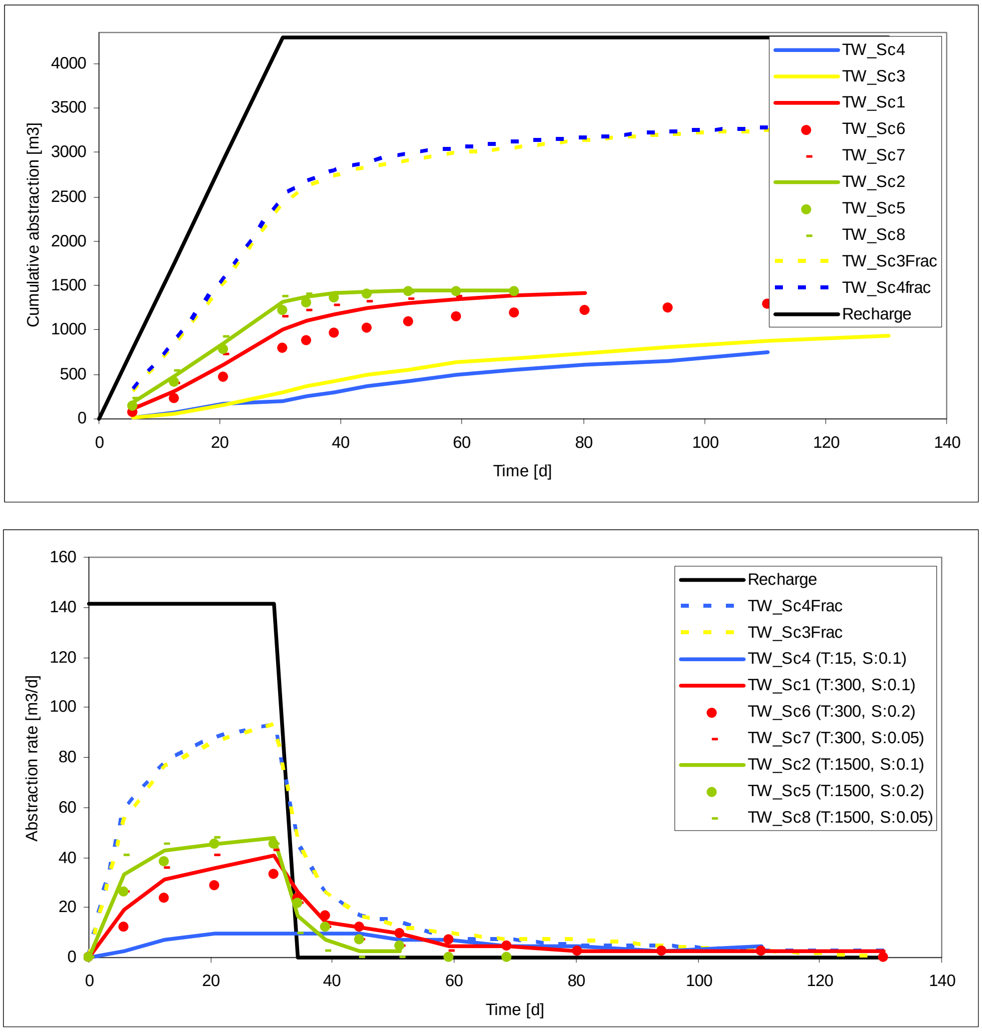


Figure 3.7 Cumulative abstraction and abstraction rate of a tube well located 110 m distance from the centre of the recharge structure in relation to total recharge.

ABILITY OF TUBE WELLS TO RECOVER RECHARGE WATER DEPENDING ON THEIR POSITION AND DEPTH

To test the impact of well location on the ability of tube wells to capture recharge water, wells have been included into the model at various locations. In scenario TW-Sc11 a well is placed at a distance of 210 m from the centre of the recharge structure, in scenario TW-Sc12 at 310 m and in scenario TW_Sc13 at 510 m, while keeping aquifer properties constant with T=300 m^2/d and S=0.1. The results show, that with increasing distance, the abstracted volume decreases from 33% of total recharge at 110 m to 4% at 510 m distance, i.e. an eight fold decrease in abstracted volume is simulated over the 400 m.

Equally important to the distance from the structure is the number of competing boreholes. An increase in the number of tube wells from 1 to 3 at 110 m distance (TW-Sc10) from the structure leads to an increase in the overall abstraction from 33% to 50% of the total recharge (Figure 3.8), however, the volume abstracted by the individual wells decreases to less than half compared to the case, when only one well is abstracting (Figure 3.12).

If two equally deep tube wells are placed downstream from each other at 110 m and 210 m from the centre of the recharge structure, the overall water recovery is 40% of total recharge, however, the borehole nearest to the recharge structure captures over two thirds of this water (TW_Sc14).

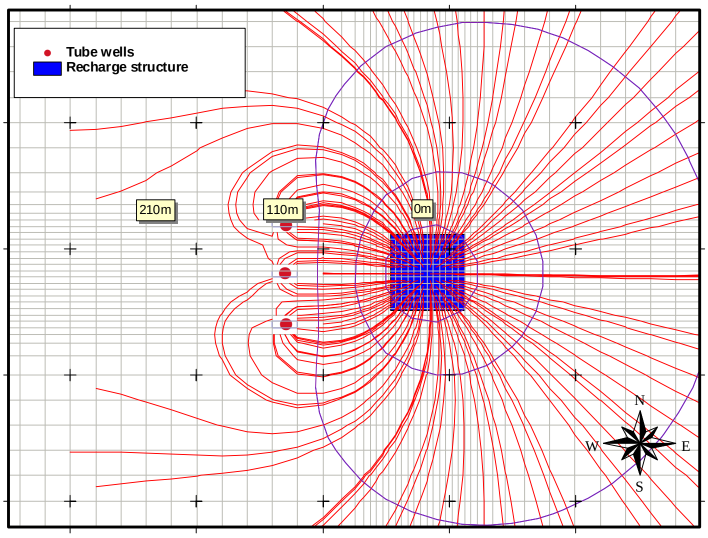


Figure 3.8 Location of tube wells in scenario TW_Sc10. Three wells are able to abstract about 50% of the total amount recharged, with abstraction volumes being equal among the individual wells.

How deepening of tube wells influences the ability of individual wells to capture recharge water is demonstrated in scenario TW-Sc15 and TW-Sc16. Doubling the depth of one of the three wells of scenario TW-Sc10 results in the deep well drawing over 80% of the total amount abstracted by all three wells in comparison to the 33% it abstracted before deepening (Figure 3.10).

Scenario TW-Sc16 illustrates the effect of deeper wells at greater distances from the recharge structure in comparison to shallow boreholes in close proximity. For this, scenario TW-Sc14 was altered, by deepening the borehole at 210 m to twice the depth of the borehole situated at 110 m from the recharge structure (Figure 3.11). This results in the deep well being able to abstract two thirds of the total volume abstracted, i.e. doubling its share of water to the detriment of the closer, but shallower well at 110 m (Figure 3.12).

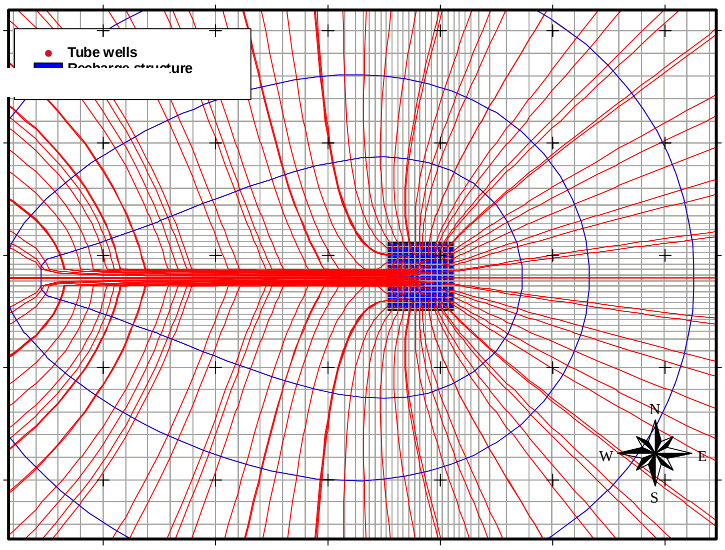


Figure 3.9 Discrete zones of higher permeability can channel recharge water, enhancing the influence of a recharge structure on water levels and abstraction volumes within the zone (Sc4frac).

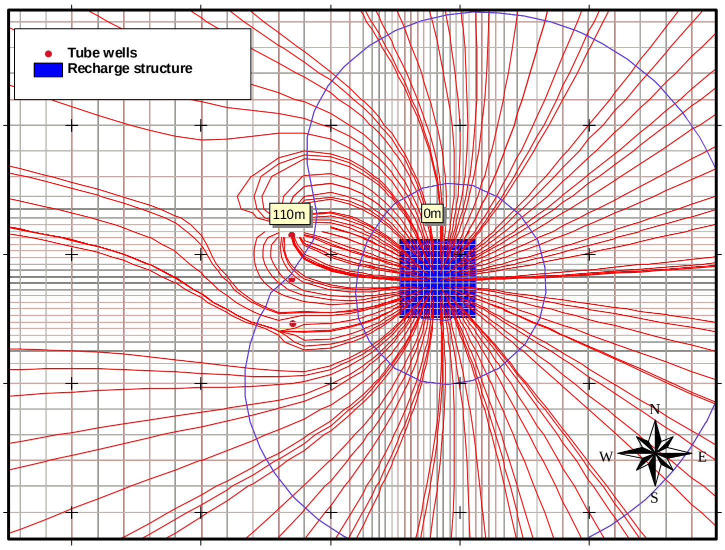


Figure 3.10 Particle tracks demonstrate the influence of depth of boreholes on their ability to abstract water, with the deep borehole the furthest north drawing over 80% of the total amount abstracted (TW-Sc15).

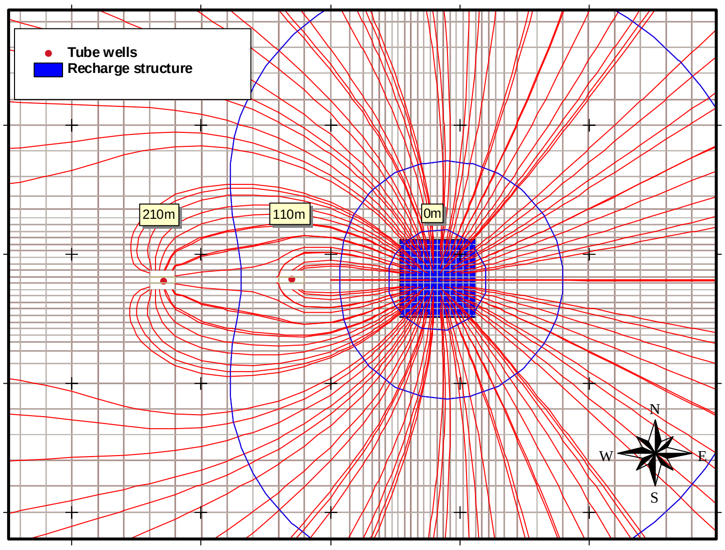


Figure 3.11 Deepening the tube well at 210 m distance results in the well being able to abstract 2/3 of the total volume abstracted, i.e. doubling its share of water to the detriment of the closer, but shallower well at 110 m distance.

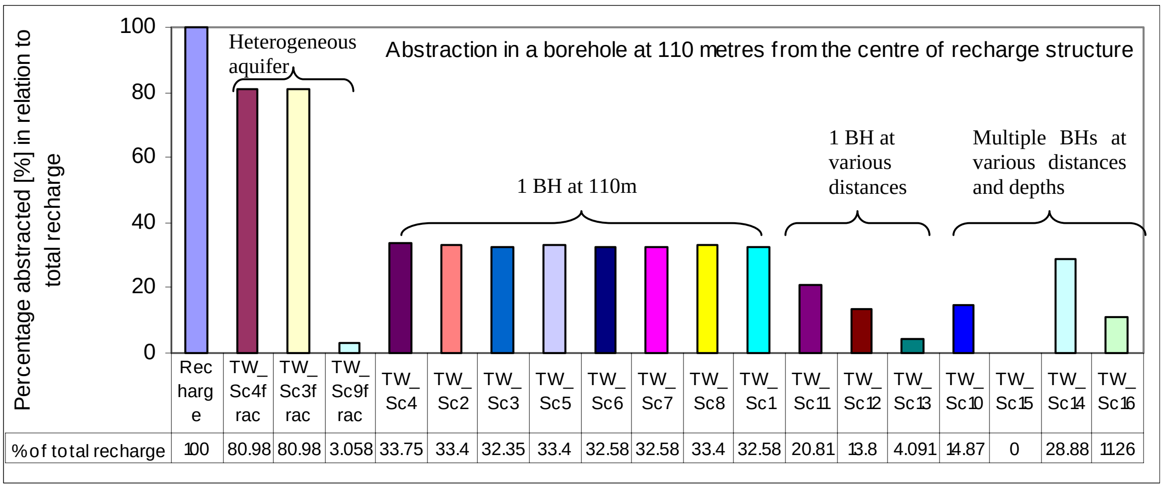


Figure 3.12 Abstraction in a tube well at 110 m distance from the recharge structure in relation to total recharge.

3.3 CONCLUSIONS

- Within the range of parameters used, the simulated impact of the recharge structure on water levels is minimal for all but the immediate vicinity of the structure itself if aquifers are isotropic and homogenous. Water level rises are of the order of centimetres, due to the recharge volume being small compared to the volume of the aquifer the recharge water occupies over time.
- The impact of a recharge structure increases the larger the ratio between recharge water volume and receiving aquifer body volume, i.e. the smaller the aquifer being

recharged, the larger the effect. Preferential flow paths in form of discrete zones of higher permeability can act as such zones, where recharge water is channelled resulting in a substantial rise in water levels, sustained over longer periods. The impact is greater, for larger differences in permeability between the aquifer and the preferential flow zone. Aquifers of limited extent could also enhance the impact of a recharge structure by allowing recharge water only to dissipate into a comparatively small aquifer volume.

- The rate at which water levels subside after recharge events depends on the aquifer parameters with levels sustained longer, the lower the aquifer permeability. Within the range of parameters used, the simulated decline in water levels to half their peak level, ranges from a few days in the case of permeable aquifers to a couple of months in the case of aquifers of low transmissivity.
- The ability of a tube well to abstract recharge water is apparently independent of aquifer properties over long time scales. High permeable aquifers allow high abstraction rates, which can be sustained over a short period, after which the tube well becomes dry, i.e. the water level in the aquifer falls below the bottom of the well. Tube wells in low conductivity material can only abstract at low rates, but can sustain this over long periods, so that the total amount abstracted in either case is the same.
- If several wells compete for water, their location and depth outweigh aquifer properties in their importance for the wells ability to abstract water under homogenous conditions. Within the range of parameters used, the simulated proportion of water able to be withdrawn by tube wells in relation to the total water recharged decreases eight fold over a 400 m distance away from the recharge structure. By deepening tube wells, their ability to capture water increases to the detriment of shallow tube wells, even if those are located in close proximity to the recharge structure.
- The intake of water is substantially increased in tube wells located in discreet zones of higher permeability with elevated abstraction rates being maintained over prolonged periods. Within the range of parameters used, the total amount abstracted in relation to the total amount recharged increases from 33% under homogenous conditions to 81% if a well is situated within a high permeable zone at 110 metres distance from the recharge structure. The effect increases, as the contrast in permeability between aquifer and preferential flow zone becomes greater.

4 Impact of artificial recharge on groundwater availability at community level

To establish if the added recharge significantly enhances the groundwater availability for a community, the hydraulic capacity of the recharge structure, which is the accumulated infiltration over a long period that includes dry periods, needs to be put into context with the overall water demand and the naturally occurring recharge in the area. This determines the overall significance of the scheme for the local rural community.

The significance of added recharge in terms of ratio between artificial recharge and total abstraction is illustrated in Table 4.1 and Figure 4.1 for different hydrological settings. A recharge structure of 30 m by 100 m, with a water column of 2 m when full, i.e. a volume of 6000 m^3 is assumed. The yearly hydraulic capacity is calculated on the basis of the number of fillings the structure receives per year (Table 4.1). Evaporation is assumed to be negligible. Abstraction around this hypothetical tank is based on boreholes abstracting 20 m^3/d for domestic supply. The total amount abstracted per community is dependent on the number of boreholes in the area (Table 4.1).

To compare the hydraulic loading of the recharge structure with the actual abstraction in the community surrounding the tank, the total tank recharge per year is given as a percentage of total abstraction per year and listed in Table 4.1 and graphed in Figure 4.1.

Table 4.1 Hydraulic loading of a hypothetical recharge structure in relation to abstraction

Number of boreholes in community	**Total abstr. (m^3/d)**	**Abstr. per year (m^3/year)**	**Tank recharge as a percentage of abstraction (%)**				
			1 filling (6000 m^3)	2 fillings (12000 m^3)	3 fillings (18000 m^3)	4 fillings (24000 m^3)	6 fillings (36000 m^3)
1	20	7300	82.19	164.38	246.58	328.77	493.15
2	40	14600	41.10	82.19	123.29	164.38	246.58
3	60	21900	27.40	54.79	82.19	109.59	164.38
4	80	29200	20.55	41.10	61.64	82.19	123.29
5	100	36500	16.44	32.88	49.32	65.75	98.63
6	120	43800	13.70	27.40	41.10	54.79	82.19
7	140	51100	11.74	23.48	35.23	46.97	70.45
8	160	58400	10.27	20.55	30.82	41.10	61.64
9	180	65700	9.13	18.26	27.40	36.53	54.79
10	200	73000	8.22	16.44	24.66	32.88	49.32
11	220	80300	7.47	14.94	22.42	29.89	44.83
12	240	87600	6.85	13.70	20.55	27.40	41.10
13	260	94900	6.32	12.64	18.97	25.29	37.93
14	280	102200	5.87	11.74	17.61	23.48	35.23
15	300	109500	5.48	10.96	16.44	21.92	32.88
16	320	116800	5.14	10.27	15.41	20.55	30.82
17	340	124100	4.83	9.67	14.50	19.34	29.01
18	360	131400	4.57	9.13	13.70	18.26	27.40
19	380	138700	4.33	8.65	12.98	17.30	25.96
20	400	146000	4.11	8.22	12.33	16.44	24.66

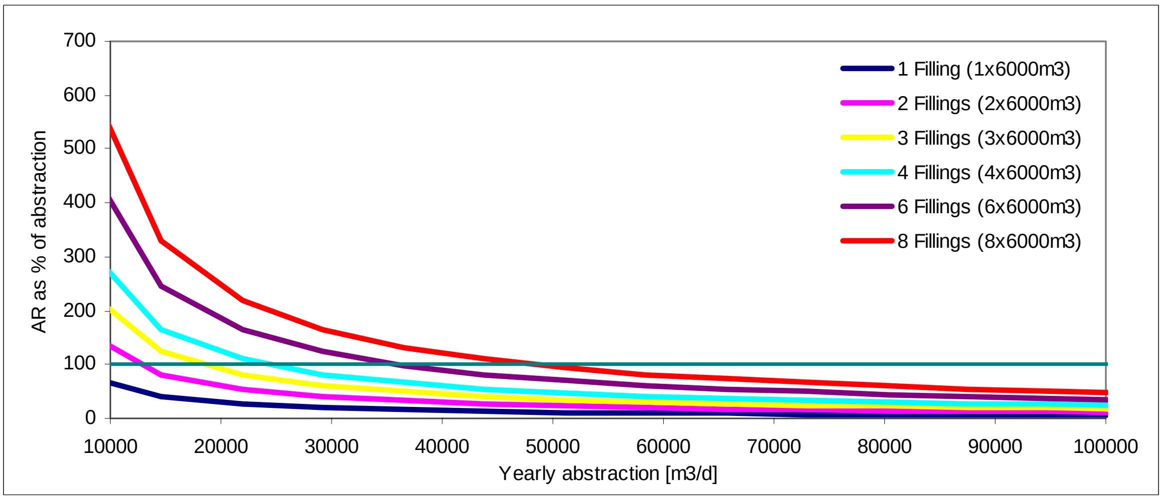


Figure 4.1 Significance of added artificial recharge (AR) in percent of yearly abstraction for various hydraulic loadings.

Figure 4.1 and Table 4.1 demonstrates the scale dependency of the structures' significance in terms of its impact on the water balance. With increasing abstraction, the percentage of discharge, which can be replaced by recharge from the tank, decreases rapidly. The horizontal line in Figure 4.1 marks the threshold, where all, i.e. 100% of abstraction could theoretically be served by artificial recharge. For low abstraction rates, this is achieved even for low hydraulic loadings. However, as abstraction increases the deficit between pumping and water supplied by artificial recharge increases even when applying high loading rates, until the percentage of water being added by the tank is insignificant compared to the amount pumped.

A similar comparison can be made between added recharge and naturally occurring recharge. For an assumed natural recharge of 100 mm/a and three different hydraulic reservoir loadings Figure 4.2 graphs the significance of added recharge (AR) as a percentage of the naturally occurring recharge for increasing catchment sizes. This illustrates that natural recharge is of much larger significance for the local water balance for low hydraulic loadings than artificial recharge, more so the larger the area receiving recharge. With increasing loading rates the share supplied by artificial recharge compared to naturally occurring recharge is generally higher, however, the larger the area an artificial recharge structure serves, the less impact it has on the water balance.

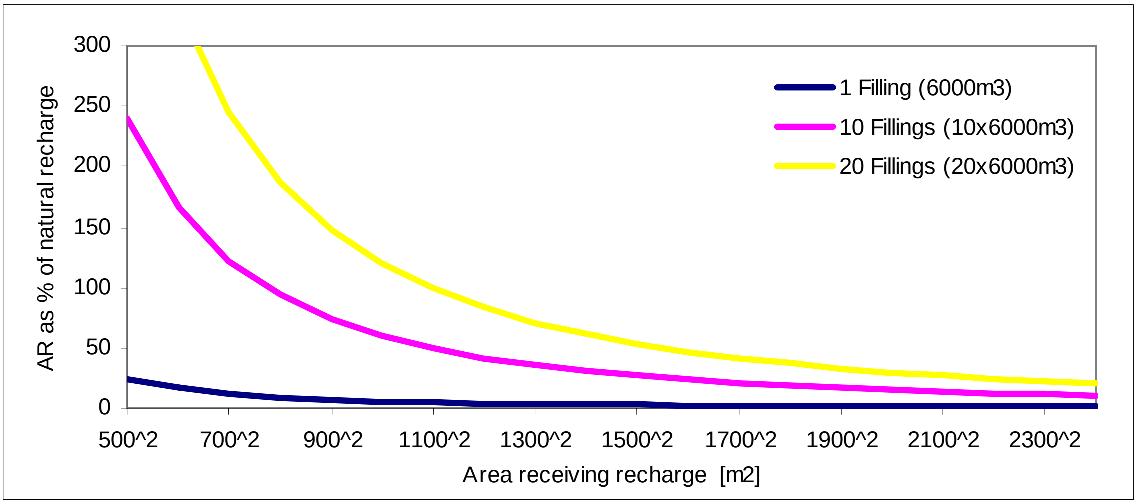


Figure 4.2 Significance of added artificial recharge (AR) in terms of % of natural occurring recharge with increasing area receiving recharge.

4.1 QUANTIFYING IMPACT OF ARTIFICAL RECHARGE STRUCTURES ON WATER BALANCE FOR INDIAN STUDY AREAS

To study the impact of a recharge structure on the groundwater availability at community level in the Indian study areas, the total volume recharged per reservoir needs to be established. Therefore, the decline in reservoir water levels, measured at every reservoir in the Indian study areas (see Section 2), needs to be converted into a recharge volume by relating the stage decline to the area over which the change in height occurs. This requires the shape of the reservoir to be known in order to formulate a relationship between surface area at a specific ponding depth and water volume.

An example is given below, using data form the Coimbatore research site (K. Palanisami et al., 2004). Water levels in three tanks in the Coimbatore research area have been measured over time in 2003. The example of the Kodangipalayam reservoir is illustrated below (Table 4.2, Figure 4.3).

Table 4.2 Data collected for the Kodangipalayam reservoir (K. Palanisami et al., 2004)

Date	Rainfall [mm]	Depth of water in reservoir [m]	Depth of water in reservoir in mAOD
25-Mar-03	0	1.051051	310.6881
26-Mar-03	0	0.990991	310.628
27-Mar-03	0	0.990991	310.628
28-Mar-03	0	0.990991	310.628
29-Mar-03	0	0.990991	310.628
30-Mar-03	0	0.960961	310.598
31-Mar-03	0	0.960961	310.598
1-Apr-03	0	0.960961	310.598
2-Apr-03	0	0.960961	310.598
3-Apr-03	0	0.960961	310.598
4-Apr-03	11	0.960961	310.598
5-Apr-03	0	0.900901	310.5379
6-Apr-03	0	0.900901	310.5379
7-Apr-03	0	0.900901	310.5379
8-Apr-03	0	0.840841	310.4778
9-Apr-03	0	0.840841	310.4778
10-Apr-03	0	0.840841	310.4778
11-Apr-03	0	0.780781	310.4178
12-Apr-03	13	0.780781	310.4178
13-Apr-03	0	0.780781	310.4178
14-Apr-03	0	0.780781	310.4178
15-Apr-03	0	0.720721	310.3577
16-Apr-03	0	0.720721	310.3577
17-Apr-03	0	0.720721	310.3577
18-Apr-03	0	0.660661	310.2977
19-Apr-03	0	0.660661	310.2977
20-Apr-03	0	0.600601	310.2376
21-Apr-03	26.2	0.600601	310.2376
22-Apr-03	0	0.540541	310.1775
23-Apr-03	0	0.540541	310.1775
24-Apr-03	0	0.48048	310.1175
25-Apr-03	0	0.48048	310.1175
26-Apr-03	0	0.42042	310.0574
27-Apr-03	0	0.42042	310.0574
28-Apr-03	0	0.36036	309.9974
29-Apr-03	12	0.36036	309.9974
30-Apr-03	36	0.36036	309.9974
1-May-03	0	0.3003	309.9373
2-May-03	0	0.24024	309.8772
3-May-03	0	0.24024	309.8772
4-May-03	0	0.18018	309.8172
5-May-03	0	0.18018	309.8172
6-May-03	0	0.09009	309.7271
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8-May-03	0	0.09009	309.7271
9-May-03	0	0	309.637

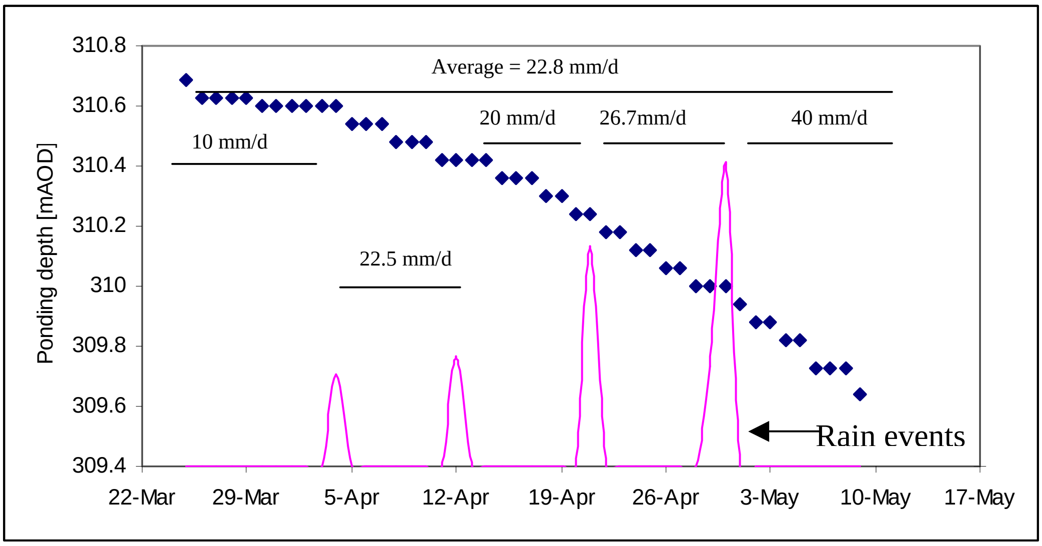
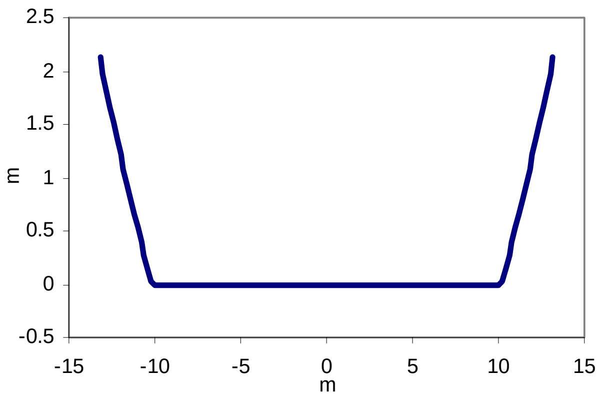


Figure 4.3 Water level drop over time in the Kodangipalayam reservoir.

The average drop in water level in the reservoir in Kodangipalayam is 22.8 mm/day. To convert this rate into a recharge volume, the relationship between the waterlevel and volume in the reservoir needs to be established. As this has not been carried out yet for the respective structure a reservoir of approximately 100 m by 20 m with the shape illustrated in Figure 4.4 is assumed.



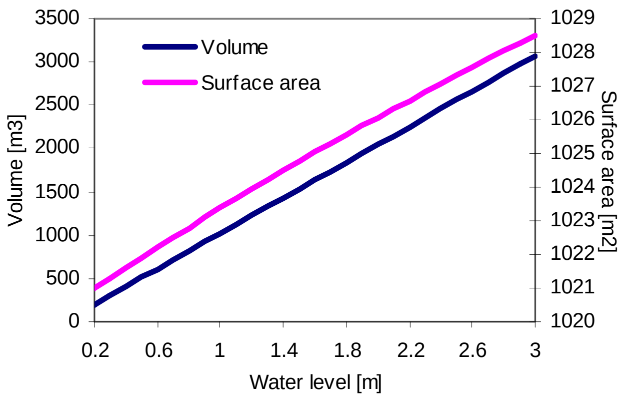


Figure 4.4 Assumed shape of reservoir and relationship between reservoir levels and water surface area and volume.

On the basis of the above, losses to recharge and evaporation, assumed to be 3.5 mm/d, can be calculated for the Kodangipalayam reservoir for periods without precipitation (dry periods) and are summarised in Table 4.3.

Table 4.3 Volumes lost to recharge and evaporation during dry periods based on the measured water level decline and the assumed shape of the Kodangipalayam reservoir.

Date	Water level in reservoir [m]	Water surface area [m^2]	Water volume in reservoir [m^3]	Volume lost to evap. (*100) [m^3/d/reservoir]	Total volume lost during dry periods [m^3]	Volume lost to recharge during dry periods [m^3]	% lost to recharge during dry periods	% lost to evaporation during dry periods
3/21/03	1.051	2023.53	2126.73	7.082	182.1	75.9	41.7	58.3
3/22/03	1.051	2023.53	2126.73	7.082				
3/23/03	1.051	2023.53	2126.73	7.082				
3/24/03	1.051	2023.53	2126.73	7.082				
3/25/03	1.051	2023.53	2126.73	7.082				
3/26/03	0.991	2023.36	2005.32	7.082				
3/27/03	0.991	2023.36	2005.32	7.082				
3/28/03	0.991	2023.36	2005.32	7.082				
3/29/03	0.991	2023.36	2005.32	7.082				
3/30/03	0.961	2023.27	1944.63	7.081				
3/31/03	0.961	2023.27	1944.63	7.081				
4/01/03	0.961	2023.27	1944.63	7.081				
4/02/03	0.961	2023.27	1944.63	7.081				
4/03/03	0.961	2023.27	1944.63	7.081				
4/04/03	0.961	2023.27	1944.63	7.081				
4/05/03	0.901	2023.10	1823.24	7.081	364.1	307.5	84.4	15.6
4/06/03	0.901	2023.10	1823.24	7.081				
4/07/03	0.901	2023.10	1823.24	7.081				
4/08/03	0.841	2022.92	1701.87	7.080				
4/09/03	0.841	2022.92	1701.87	7.080				
4/10/03	0.841	2022.92	1701.87	7.080				
4/11/03	0.781	2022.75	1580.50	7.080				
4/12/03	0.781	2022.75	1580.50	7.080				
4/13/03	0.781	2022.75	1580.50	7.080	364.0	300.3	82.5	17.5
4/14/03	0.781	2022.75	1580.50	7.080				
4/15/03	0.721	2022.57	1459.15	7.079				
4/16/03	0.721	2022.57	1459.15	7.079				
4/17/03	0.721	2022.57	1459.15	7.079				
4/18/03	0.661	2022.39	1337.80	7.078				
4/19/03	0.661	2022.39	1337.80	7.078				
4/20/03	0.601	2022.21	1216.47	7.078				
4/21/03	0.601	2022.21	1216.47	7.078				
4/22/03	0.541	2022.03	1095.15	7.077	487.2	430.6	88.4	11.6
4/23/03	0.541	2022.03	1095.15	7.077				
4/24/03	0.48	2021.85	971.81	7.076				
4/25/03	0.48	2021.85	971.81	7.076				
4/26/03	0.42	2021.66	850.51	7.076				
4/27/03	0.42	2021.66	850.51	7.076				
4/28/03	0.36	2021.48	729.23	7.075				
4/29/03	0.36	2021.48	729.23	7.075				
4/30/03	0.36	2021.48	729.23	7.075	729.2	665.6	91.3	8.7
5/01/03	0.3	2021.29	607.95	7.075				
5/02/03	0.24	2021.10	486.68	7.074				
5/03/03	0.24	2021.10	486.68	7.074				
5/04/03	0.18	2020.91	365.43	7.073				
5/05/03	0.18	2020.91	365.43	7.073				
5/06/03	0.09	2020.62	183.57	7.072				
5/07/03	0.09	2020.62	183.57	7.072				
5/08/03	0.09	2020.62	183.57	7.072				
5/09/03	0	2020.33	0.00	0.000				

For the assumed reservoir shape, recharge over the entire observation period amounts to 1780 m^3, which is 83.7 % of the total water volume lost from the reservoir (2126 m^3). In this case nearly 20 % of reservoir water is lost to evaporation.

After establishing the volume lost to recharge per reservoir filling, as illustrated in the example above, this is put into context with natural recharge volumes and local abstraction volumes in the community surrounding the recharge structure. This information is shown in Table 4.4 for the Kodangipalayam watershed, with population and catchment area data taken from K. Palanisami et al. (2004). Pumping volumes in the area are unknown but are estimated on the basis of consumption per capita, while natural recharge is assumed to be 100 mm/a.

Table 4.4 Estimate of impact of artificial recharge in terms of its percentage to pumping and its percentage to natural recharge in the Kodangipalayam watershed.

	Hydraulic loading	**Pumping [Population = 5696]**			**Nat. recharge [area = 1767 Ha]**
	m^3/year	25 l/c/d	50 l/c/d	75 l/c/d	100 mm/a
		51976 m^3/year	103952 m^3/year	155928 m^3/year	1767000 m^3/year
1 Filling	1780	*3.4 %*	*1.7 %*	*1.1 %*	*0.1 %*
2 Filling	3560	*6.8 %*	*3.4 %*	*2.3 %*	*0.2 %*
3 Filling	5340	*10.3 %*	*5.1 %*	*3.4 %*	*0.3 %*
4 Filling	7120	*13.7 %*	*6.8 %*	*4.6 %*	*0.4 %*
5 Fillings	8900	*17.1 %*	*8.6 %*	*5.7 %*	*0.5 %*
6 Fillings	10680	*20.5 %*	*10.3 %*	*6.8 %*	*0.6 %*

Due to the limited data available on natural recharge and pumping rates for the Kodangipalayam watershed, the figures given in Table 4.4 only reflect order of magnitudes on the share of artificial recharge to total pumping volumes and naturally occurring recharge, expressed in percent. Within the range of parameters used, artificial recharge can account for up to 20.5 % of total abstraction if the most favourable case is considered, with lowest water consumption per capita and highest hydraulic loadings of the reservoir. In the worst case scenario this share is down to 1.1 % (Table 4.4). Natural recharge is outweighing artificial recharge in all cases and artificially added recharge remains even for high loading rates below 1% of total recharge.

5 Summary and Conclusions

Based on work carried out during the DFID funded project "Augmentation of Groundwater by Artificial Recharge" (AGRAR) focusing mainly on low-technology recharge schemes in India, it was found, that technical effectiveness of artificial recharge structures needs to be evaluated on three levels. On a recharge basin scale, the rate of infiltration in relation to evaporation needs to be established. This determines whether the structure is fit for the purpose and can be approximated by measurements of water level declines in reservoirs during periods of no inflow and outflow except for recharge and evaporation loss. In a second step, the area of benefit, i.e. the zone of impact of the artificial recharge structure needs to be approximated, which is dependant on time scale and hydrogeological conditions at the site. This will establish the likely beneficiaries of the scheme. Thirdly, the hydraulic capacity, which is the accumulated infiltration over a long period that includes dry periods needs to be put into context with the overall water demand and the naturally occurring recharge in the area. This determines the overall significance of the scheme for the local rural community. Conclusions drawn from the evaluation of the impact of artificial recharge schemes at the three scales described above can be summarised as follows:

Reservoir scale

- During periods, where there is no precipitation, no losses due to leakage or abstraction and when the reservoir is under effluent conditions, the decline in reservoir stage levels is a function of recharge and evaporation loss only. Under such conditions the balance between evaporation and groundwater recharge will determine the effectiveness of the artificial recharge scheme. This balance can be estimated from reservoir water level declines over time.
- Decline rates serve as a good indicator for the reservoir's efficiency in recharging the aquifer. Generally, the faster the water level declines, the less water is lost to evaporation and the more efficient the reservoir recharges the aquifer.
- Various factors can affect the reservoir level decline rates. Decreasing hydraulic gradients due to a rise in groundwater levels can lead to a gradual decrease in decline rates. The same can be observed if suspended solids in the recharge water lead to an increase in reservoir bed thickness and/or a decrease in permeability over time. Reservoir shapes can influence decline rates also.
- Data from Indian case sites suggest decline rates vary widely for different reservoirs. Decline rates as low as 3.5 mm/d suggest some reservoirs to be 100% inefficient, acting basically as evaporation pans. Rates as high as 24mm/d for other reservoirs suggest a considerable loss due to recharge.

Aquifer scale

- Within the range of parameters used in the modelling study, the impact of the simulated recharge structure on water levels is minimal for all but the immediate vicinity of the structure itself if aquifers are isotropic and homogenous. Water level rises remain in the order of centimetres, due to the recharge volume being small compared to the volume of the aquifer the recharge water occupies over time.
- The impact of a recharge structure increases the larger the ratio between recharge water volume and receiving aquifer body volume, i.e. the smaller the aquifer being

recharged, the larger the effect. Preferential flow paths in the form of discrete zones of higher permeability can act as such zones, where recharge water is channelled resulting in a substantial rise in water levels, sustained over longer periods.

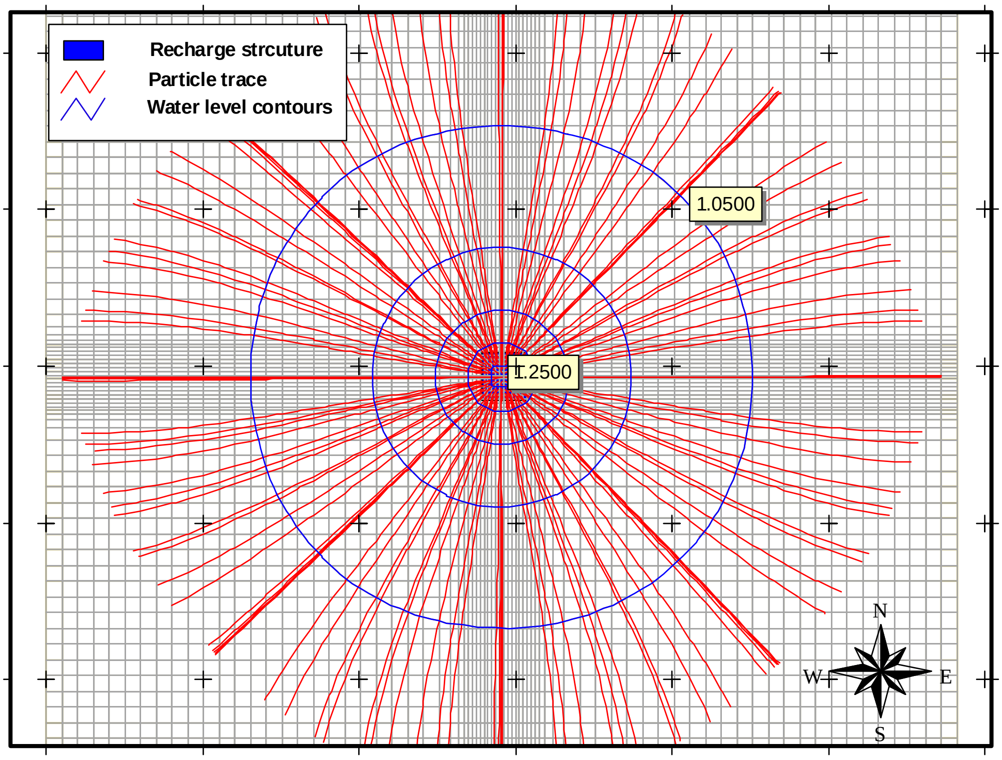
- The rate at which water levels subside after recharge events depends on the aquifer parameters with levels sustained longer, the lower the aquifer permeability.
- The ability of a tube well to abstract recharge water is apparently independent of aquifer properties over long time scales, when a homogeneous aquifer is considered. High permeable aquifers allow high abstraction rates, which can be sustained over a short period. Tube wells in low conductivity material can only abstract at low rates, but can sustain this over long periods. The intake of water is substantially increased in tube wells located in discreet zones of higher permeability with elevated abstraction rates being maintained over prolonged periods. The effect increases as the contrast in permeability between the aquifer and preferential flow zone becomes greater.
- If several wells compete for water, their location and depth outweigh aquifer properties in their control for the wells ability to abstract water in homogenous aquifers.

Community scale

- A recharge structures' significance for the groundwater availability at community level is strongly scale dependent. Generally, the larger the community the structure serves, the more insignificant the contribution from the recharge structures becomes. The deficit between added recharge and pumping volume increases with increasing abstraction. So is the deficit between added recharge and naturally occurring recharge for increasing catchment areas. For small communities with low pumping volumes, occupying a small area, artificial recharge can be a significant component of the water balance, even for low hydraulic reservoir loadings compared to local abstraction as well as naturally occurring recharge.

Appendix 1 Particle tracks under steady state conditions for all MODFLOW scenario runs

(Contour levels are shown in yellow boxes)



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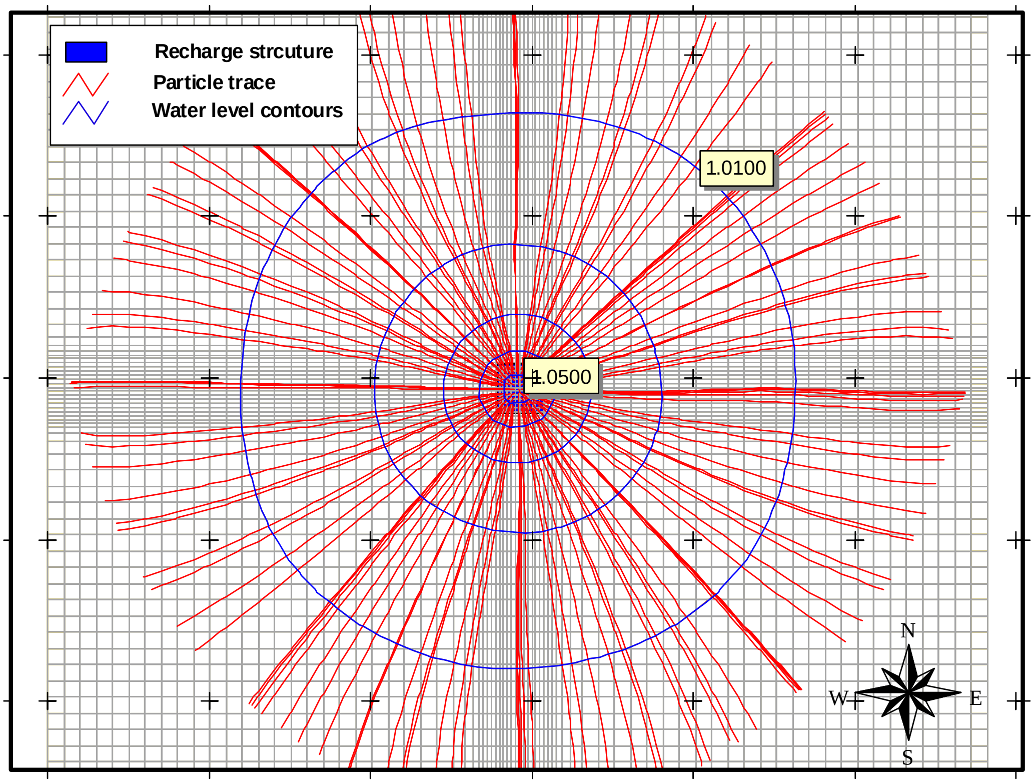

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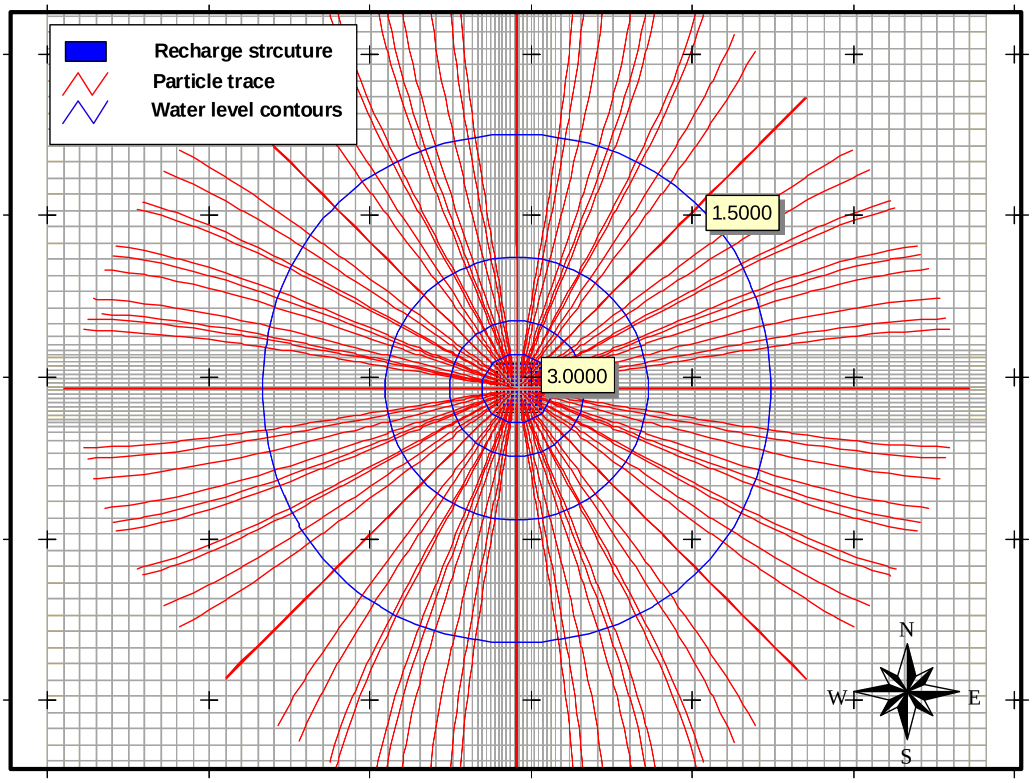
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W
E
S

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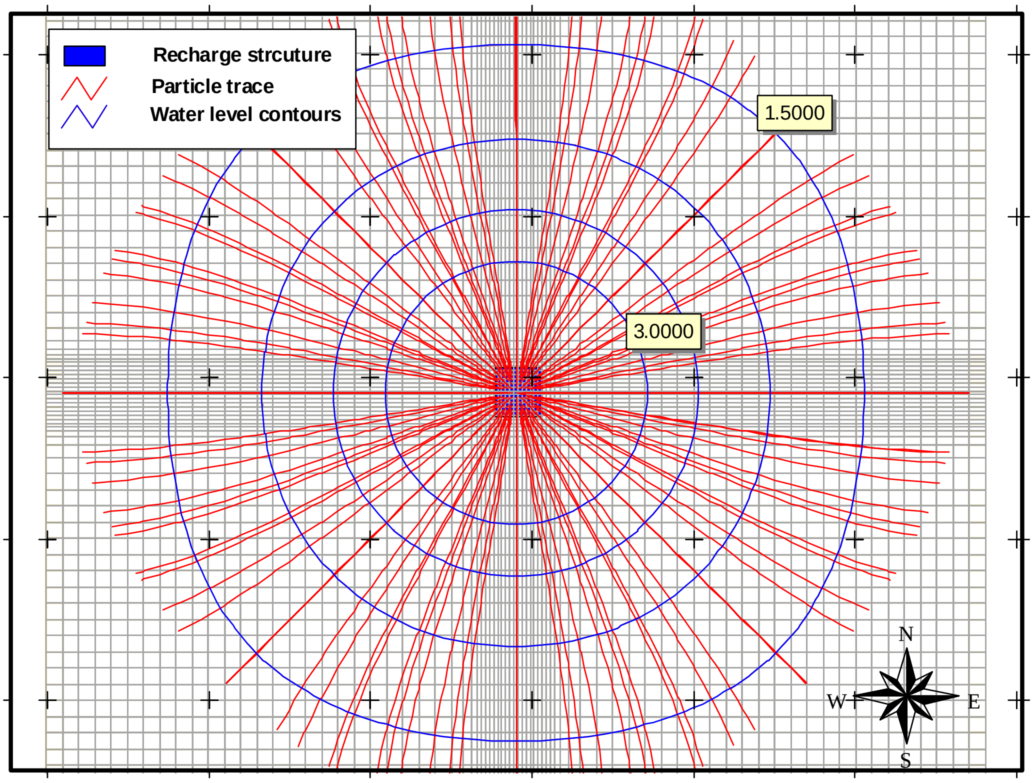
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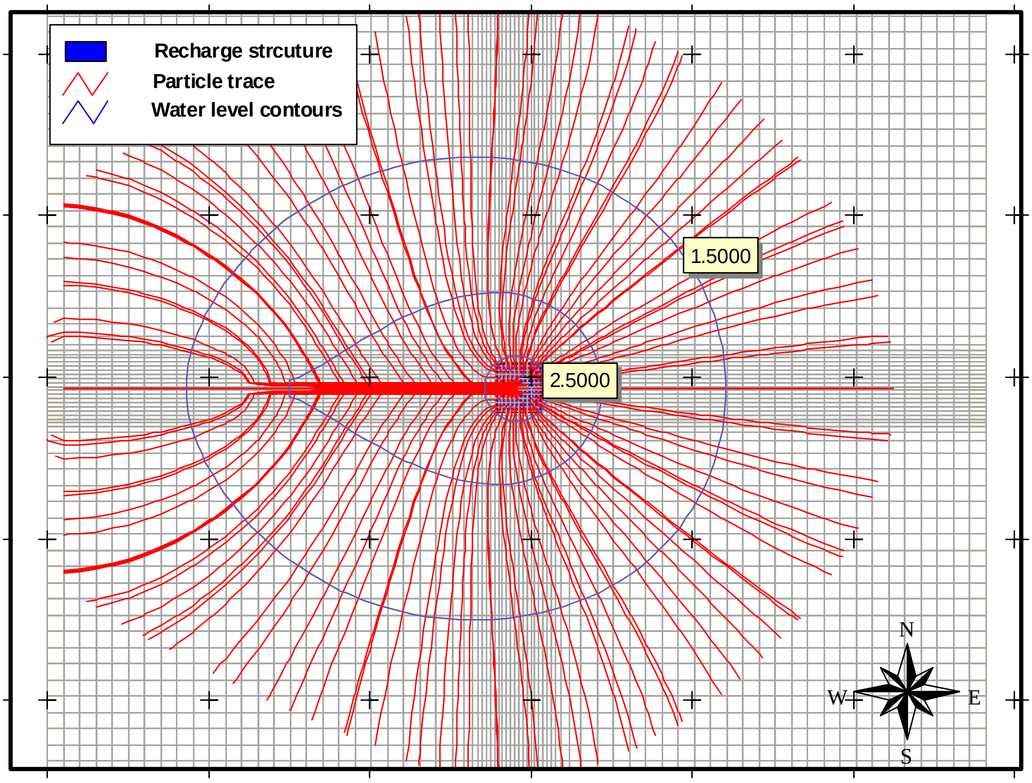

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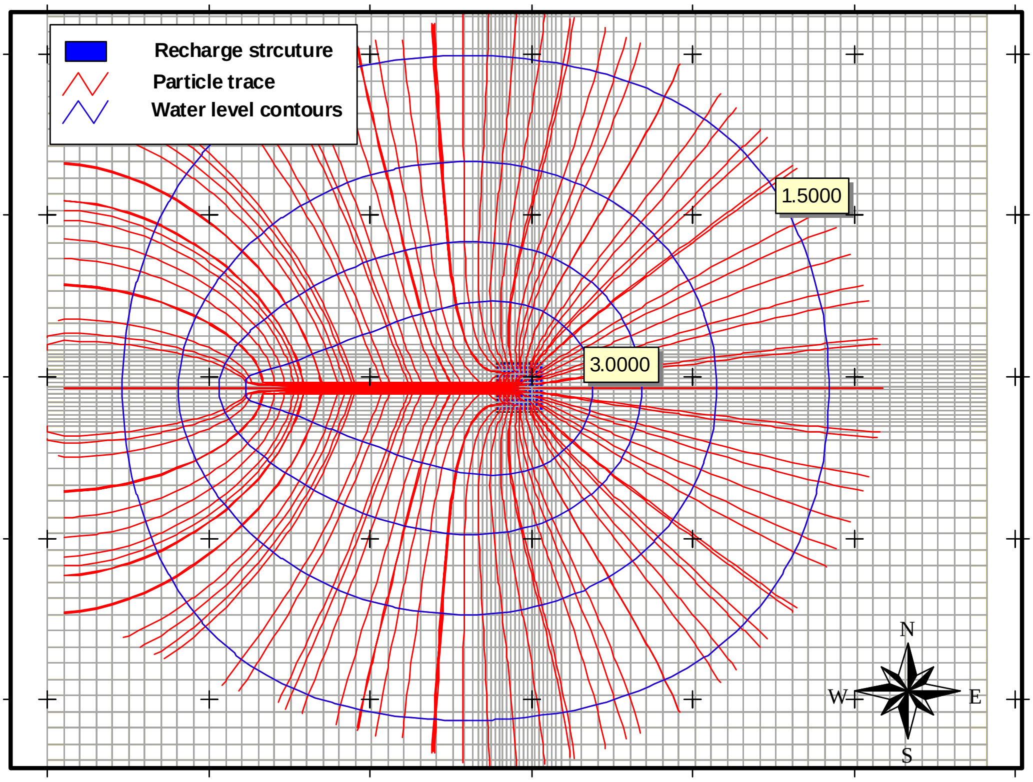

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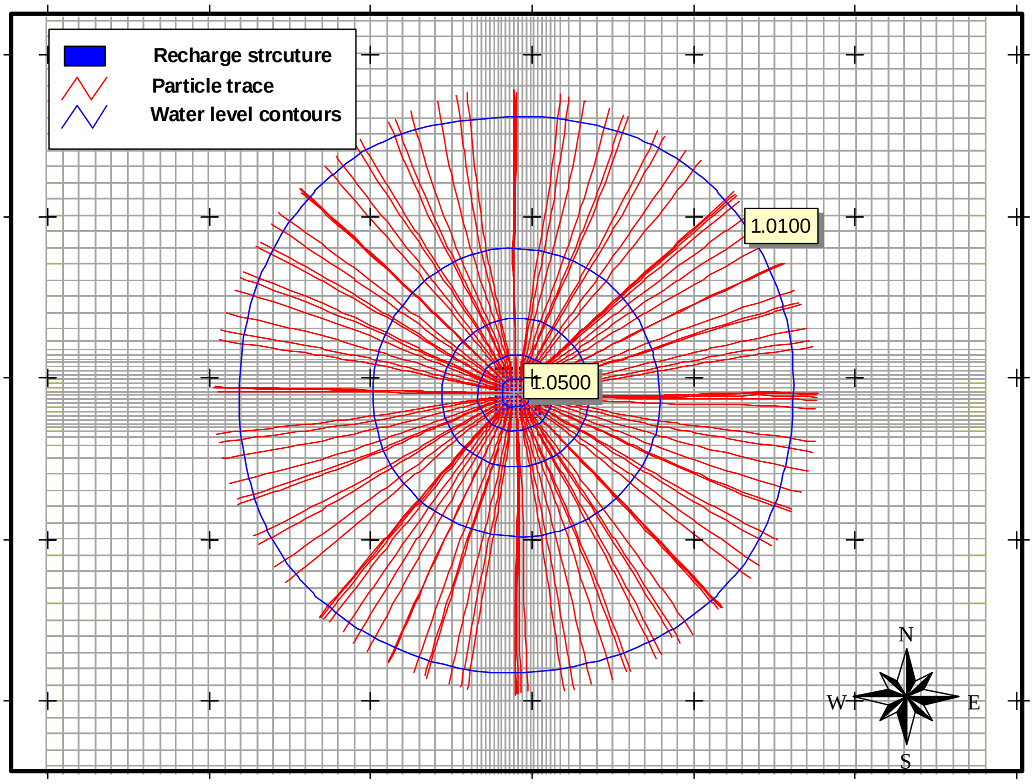
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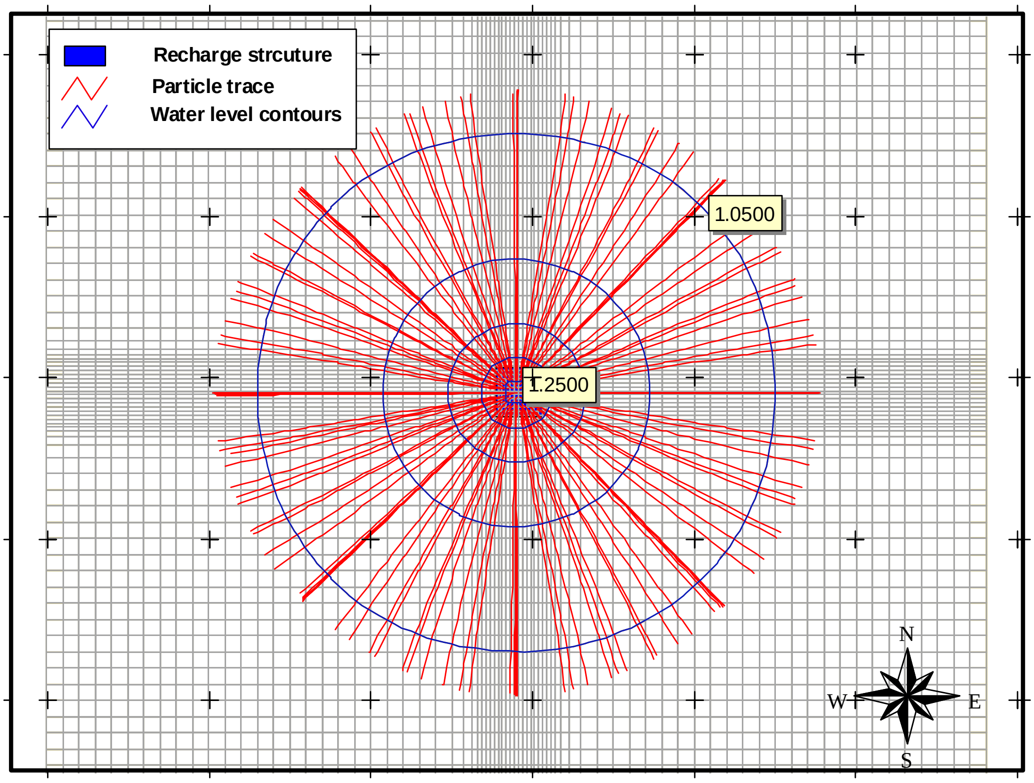
Sc5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Water level contours
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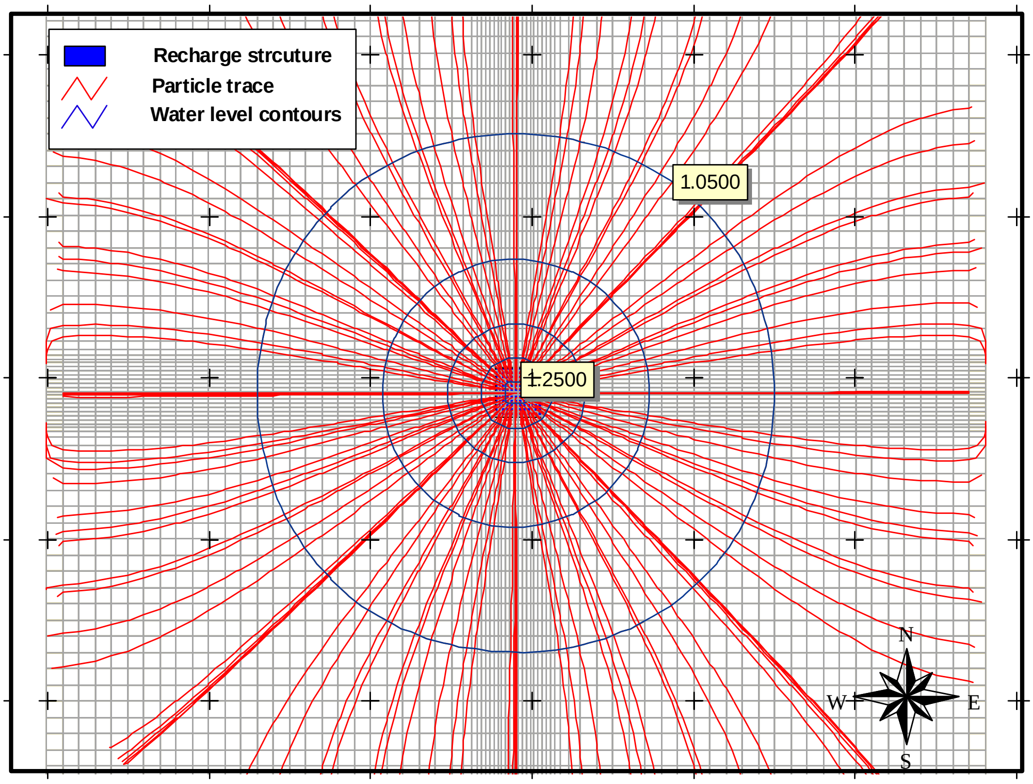
Sc6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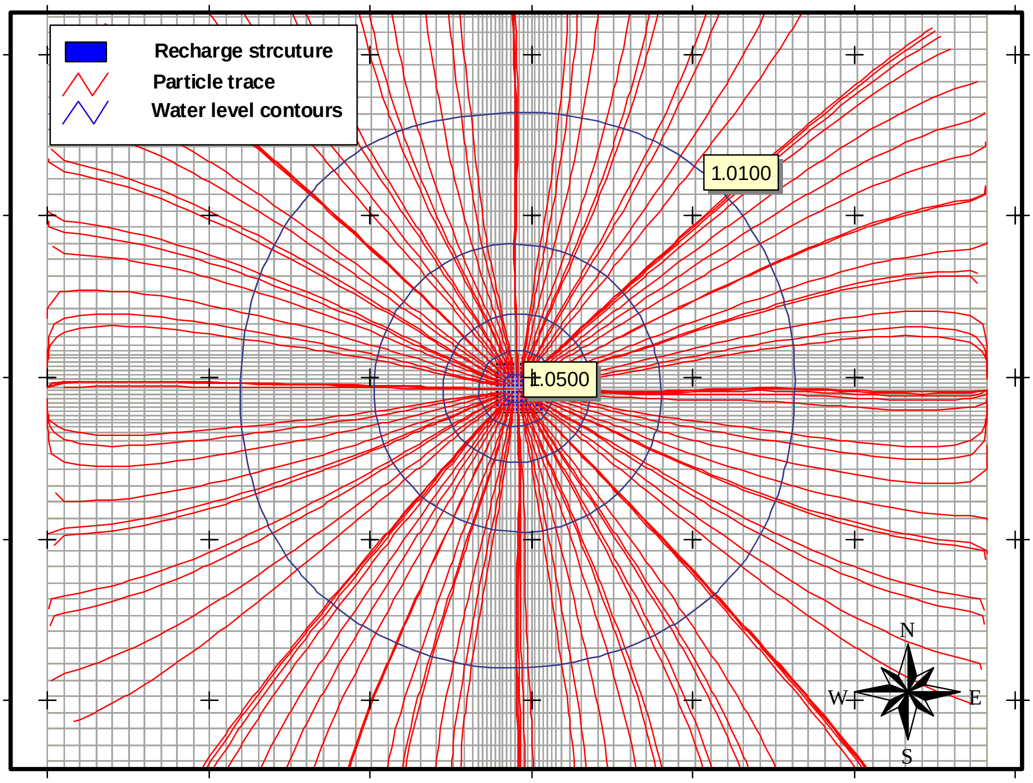
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Particle trace
Water level contours
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E
S

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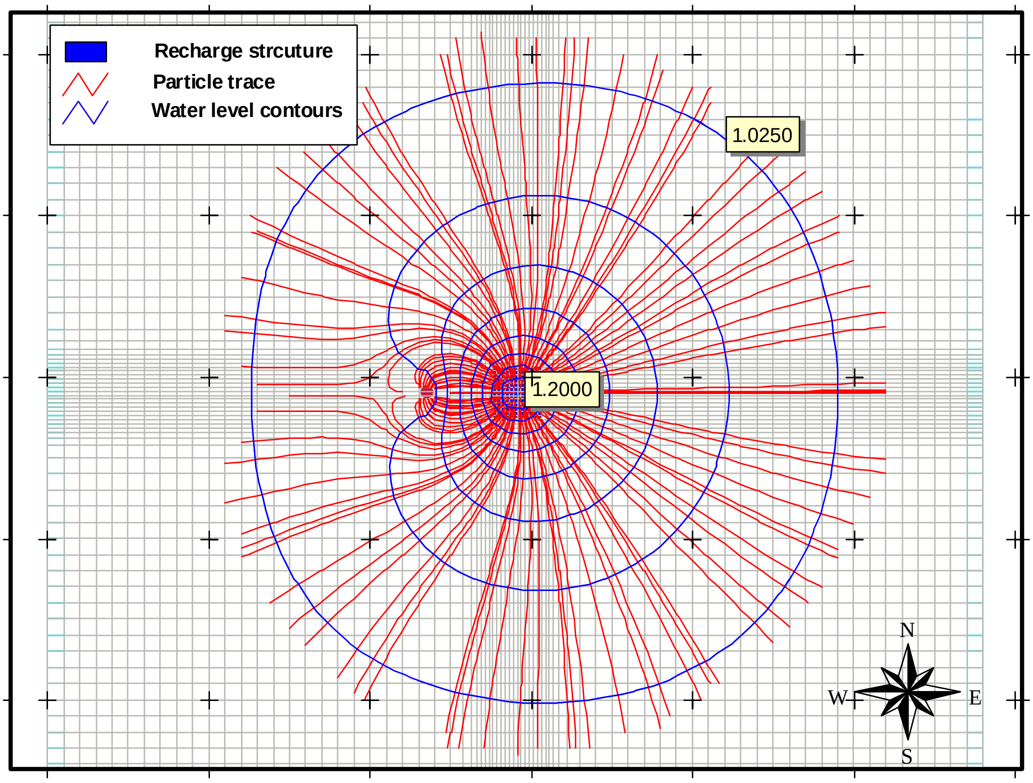

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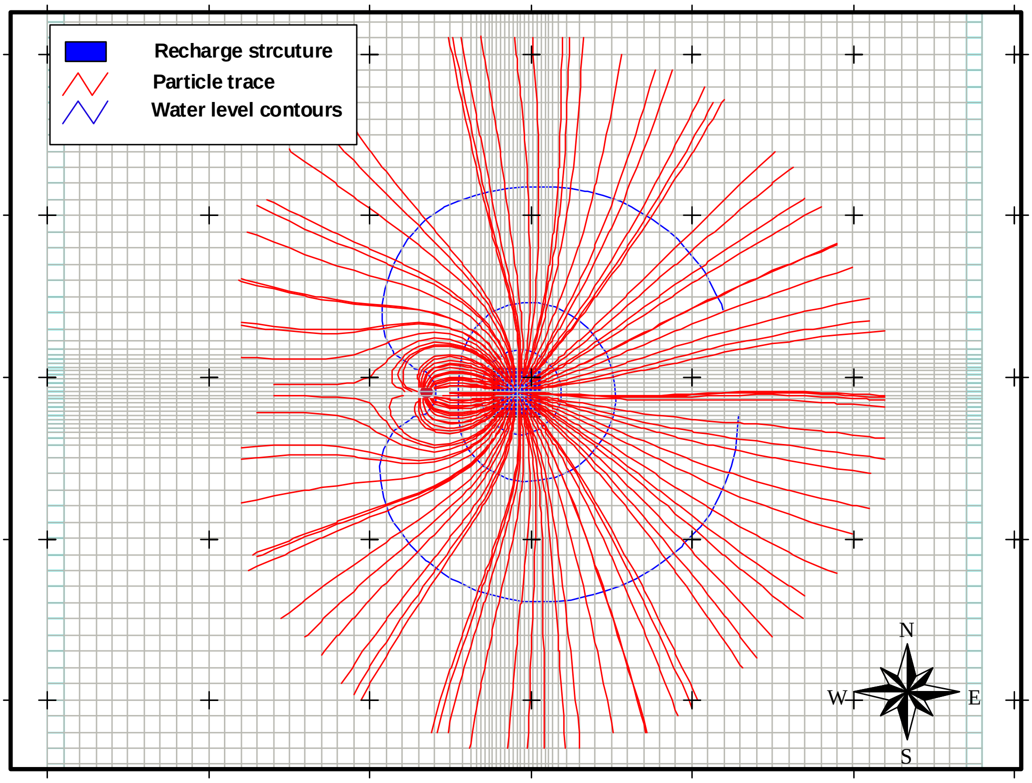
TW-Sc1



Recharge strcuture
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Water level contours
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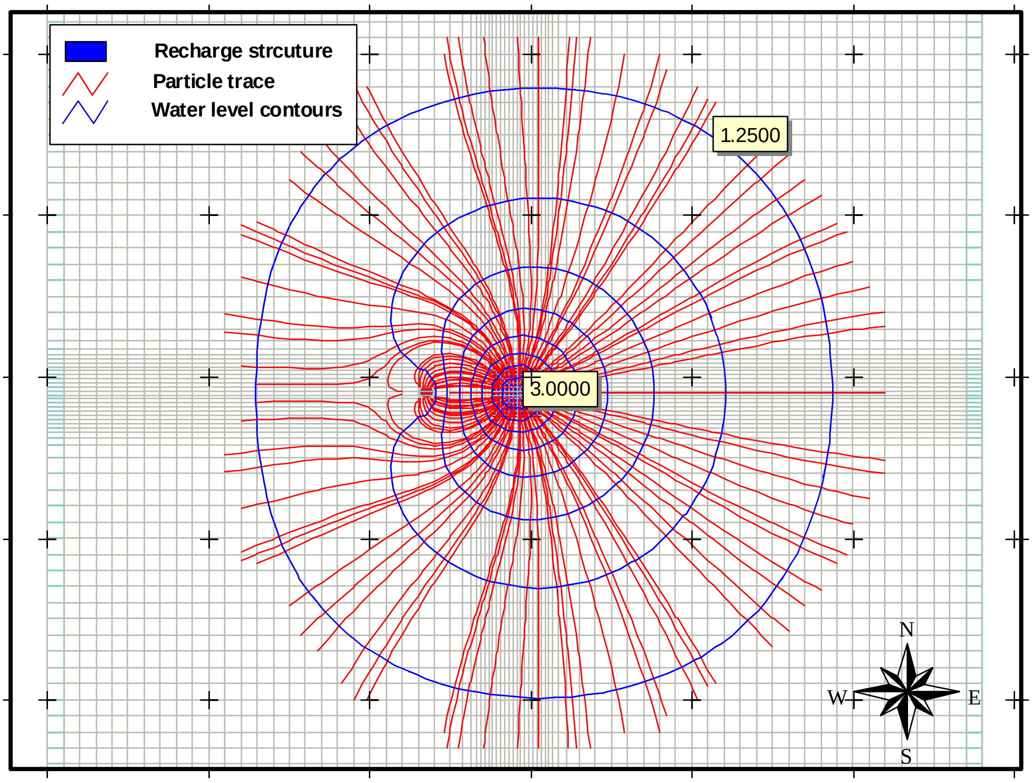
S

TW-Sc2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S

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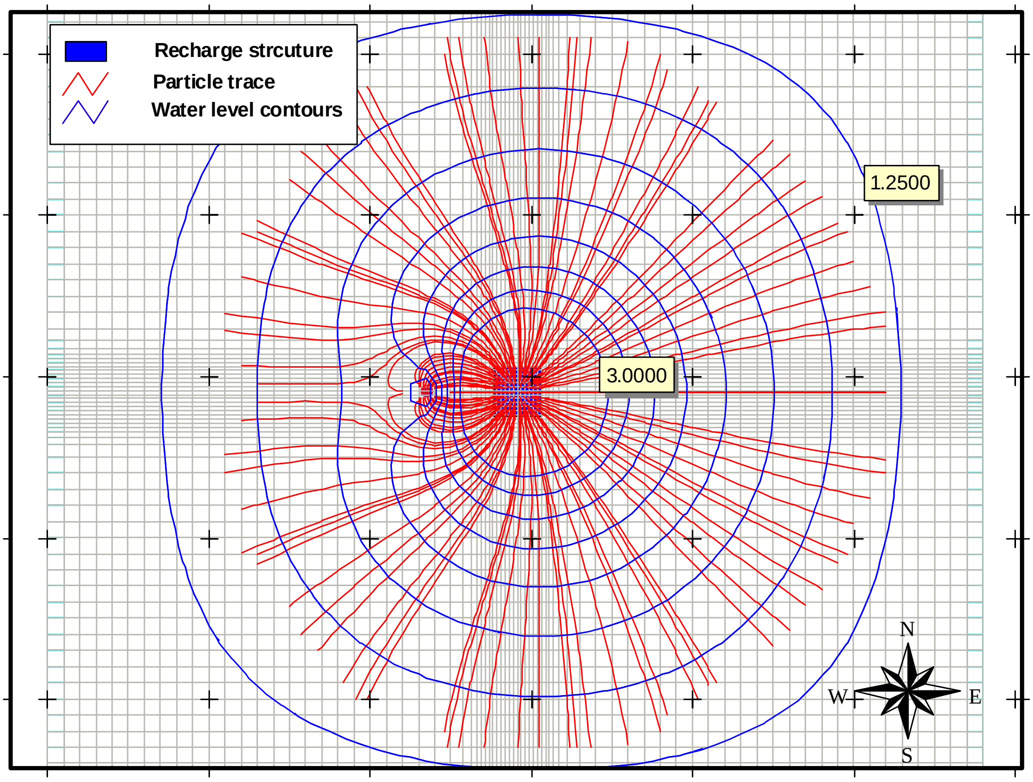
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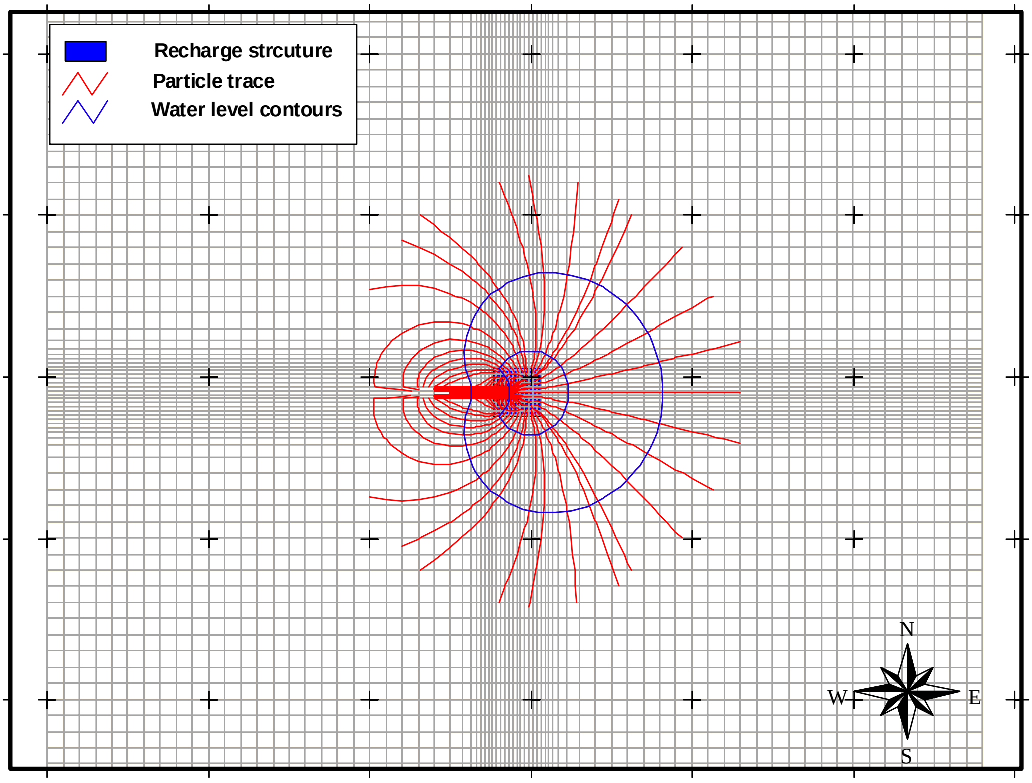

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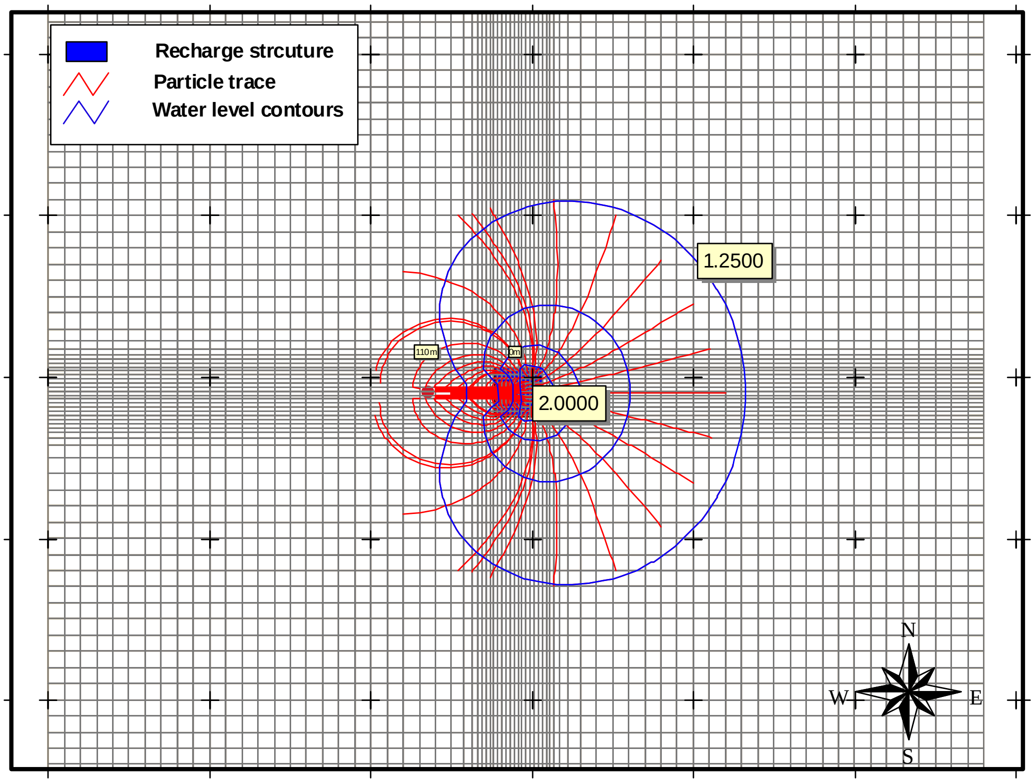

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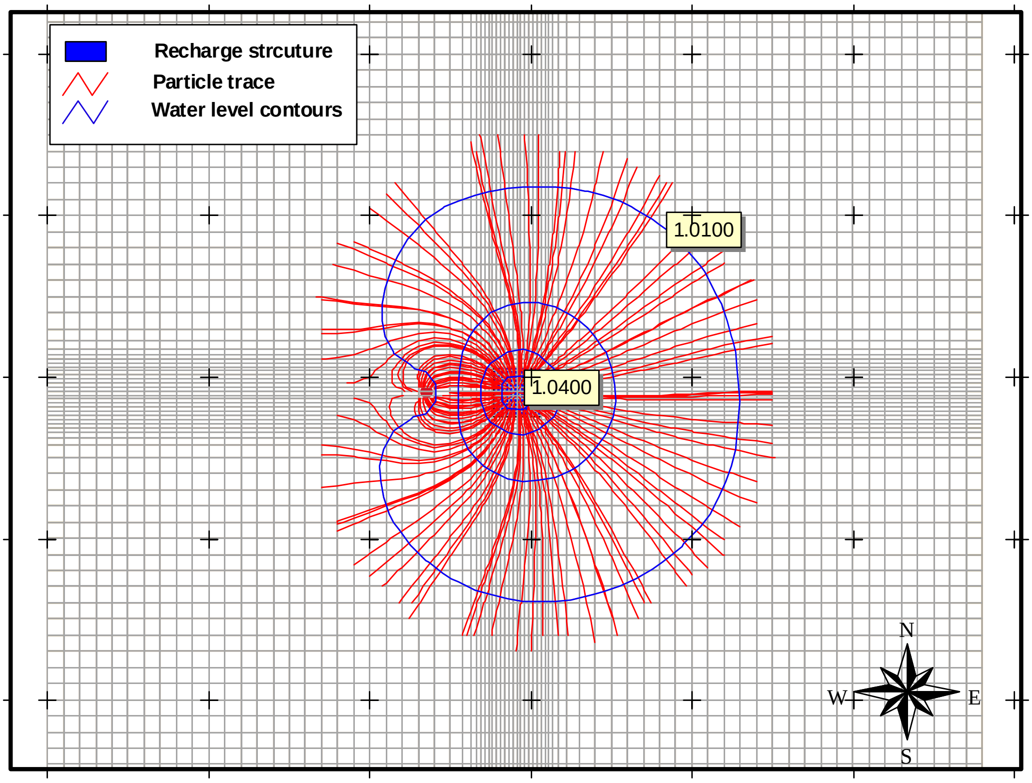
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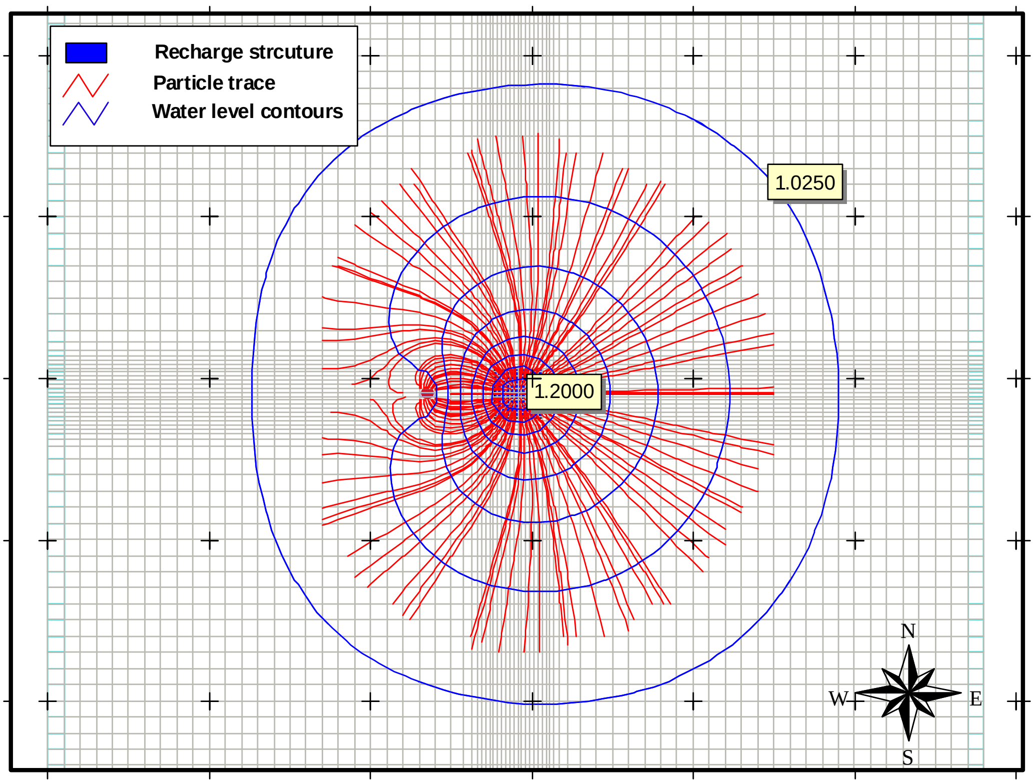
TW-Sc5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Particle trace
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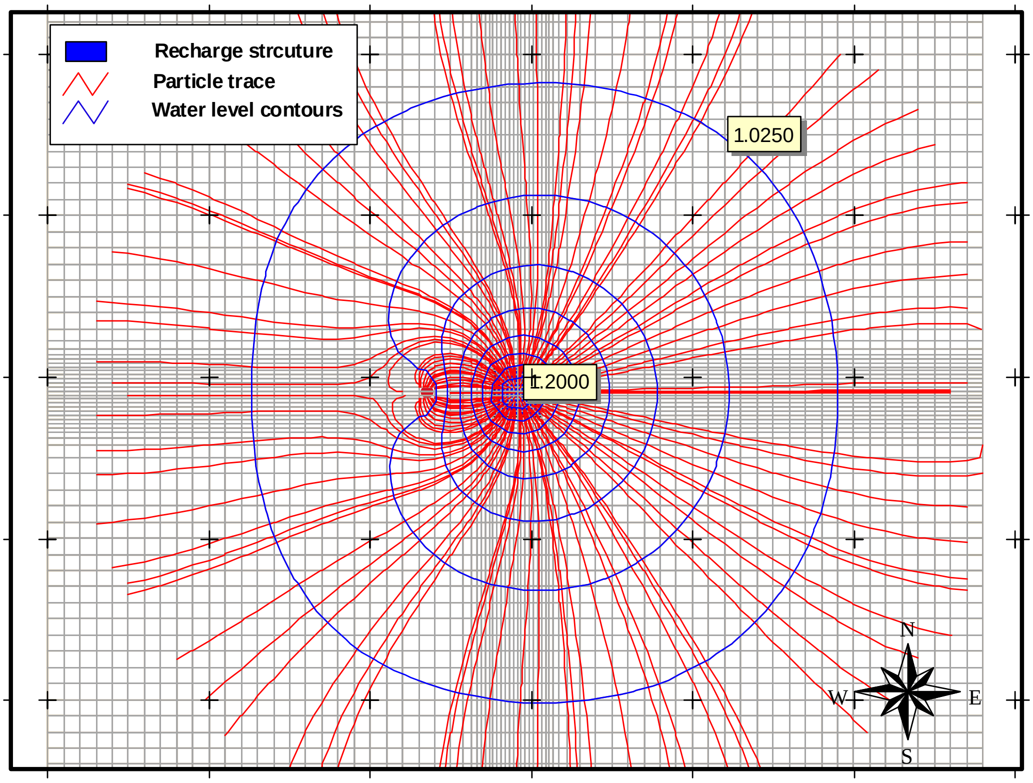
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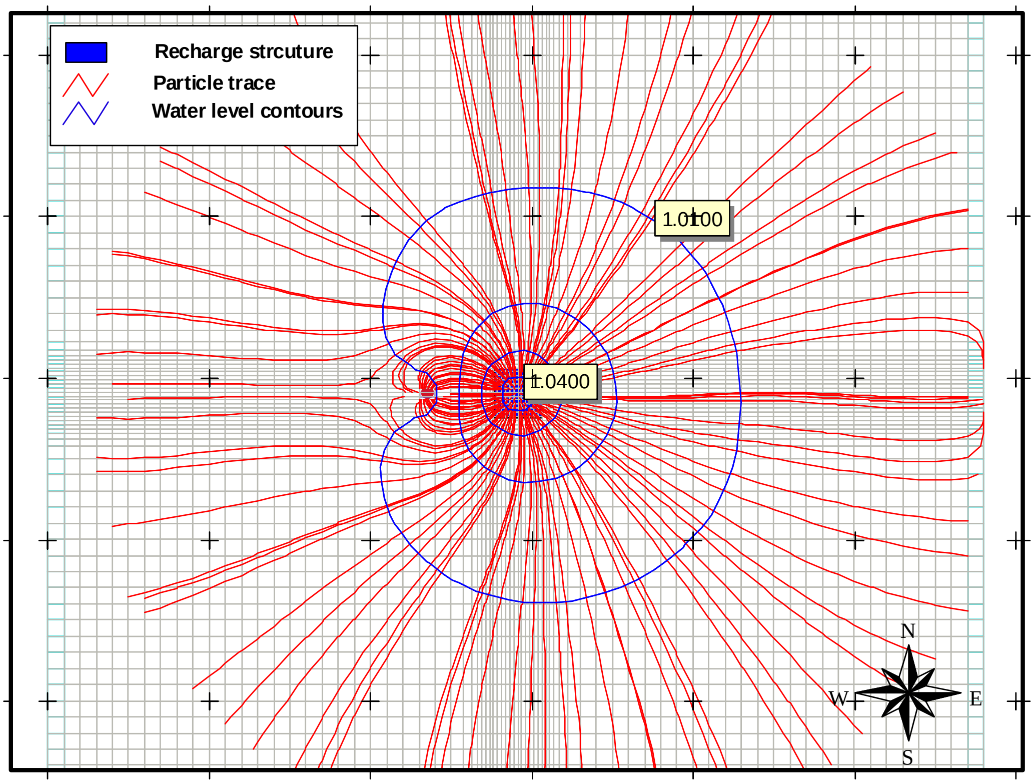
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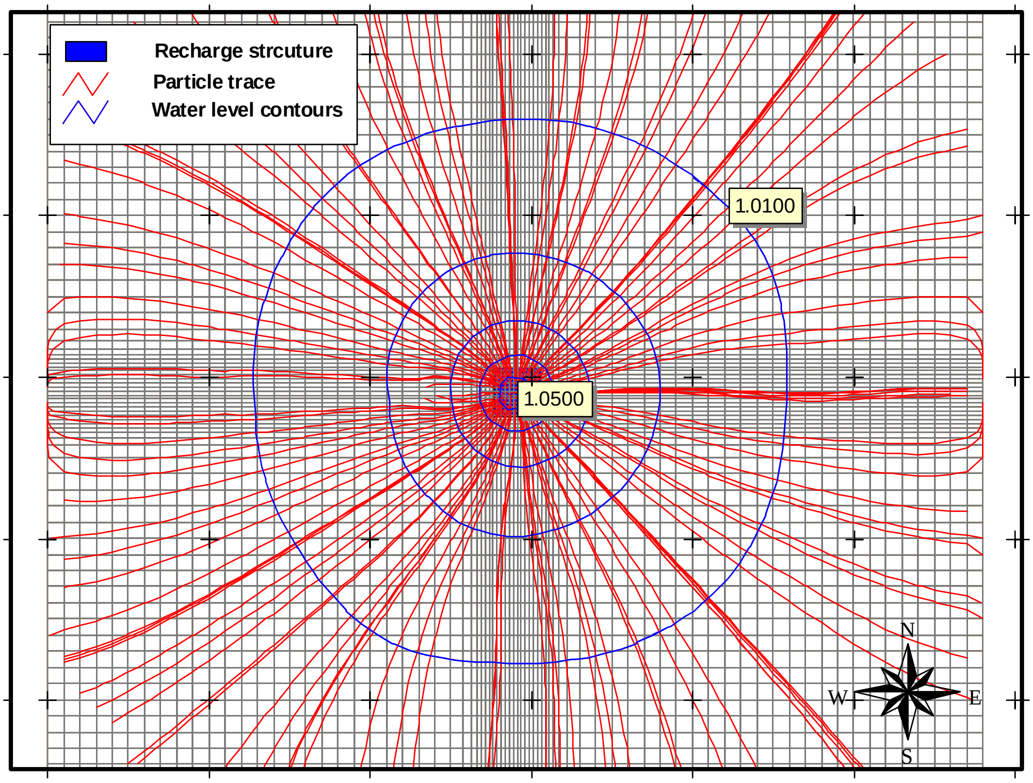
S

TW-Sc8



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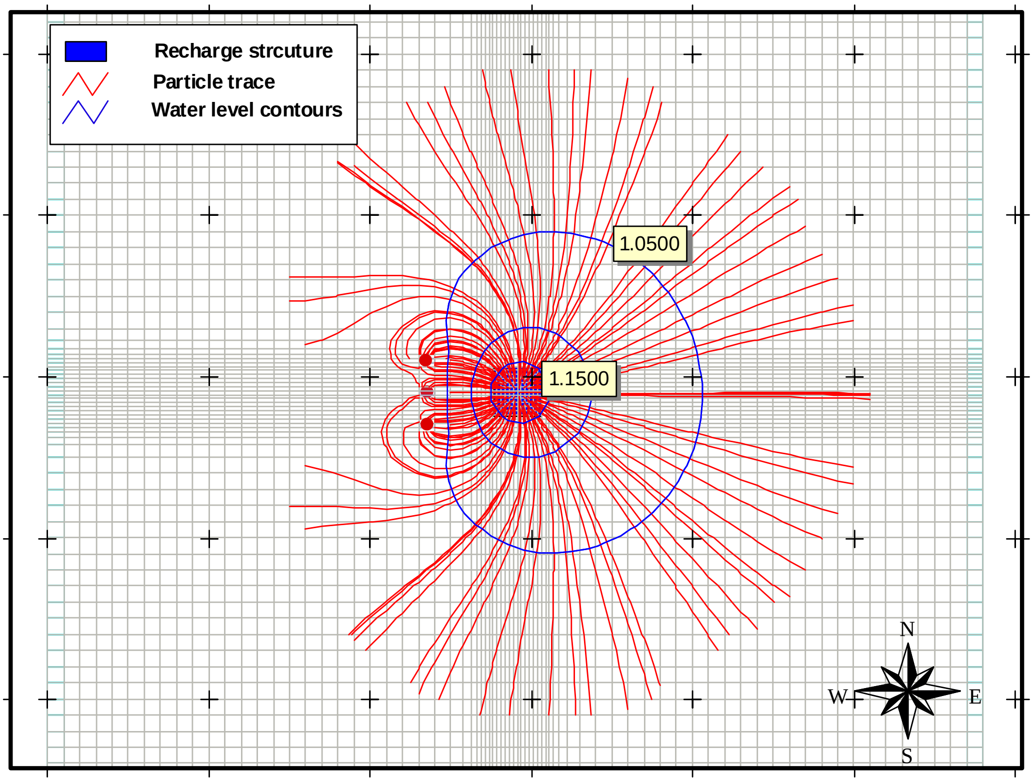

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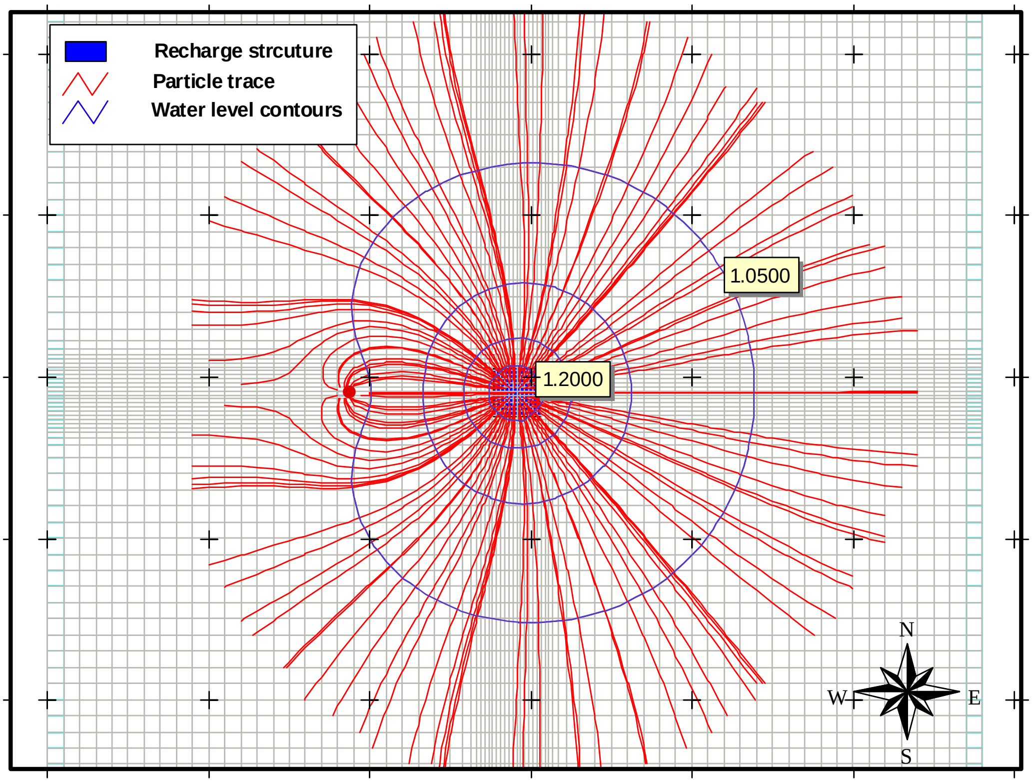

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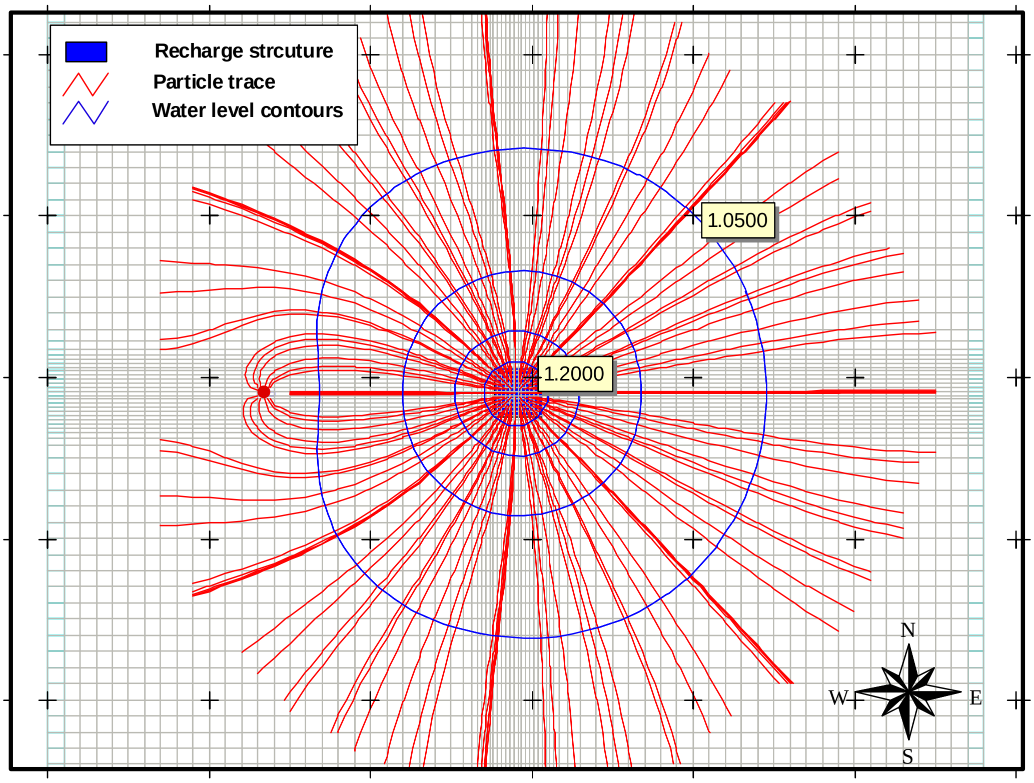

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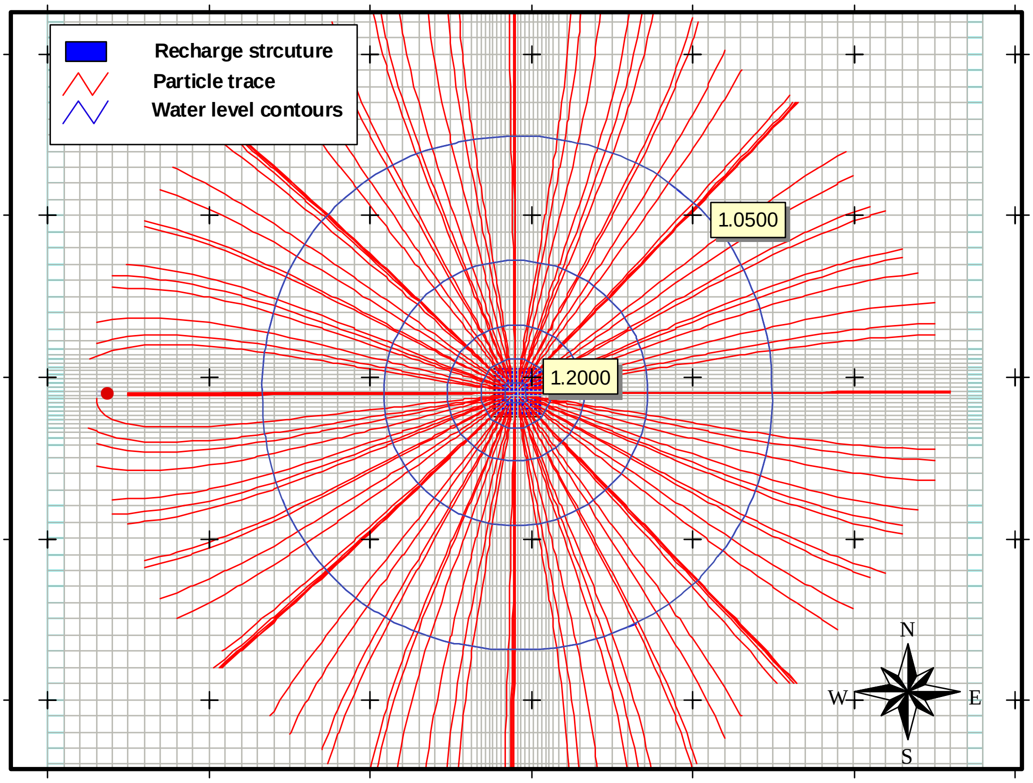

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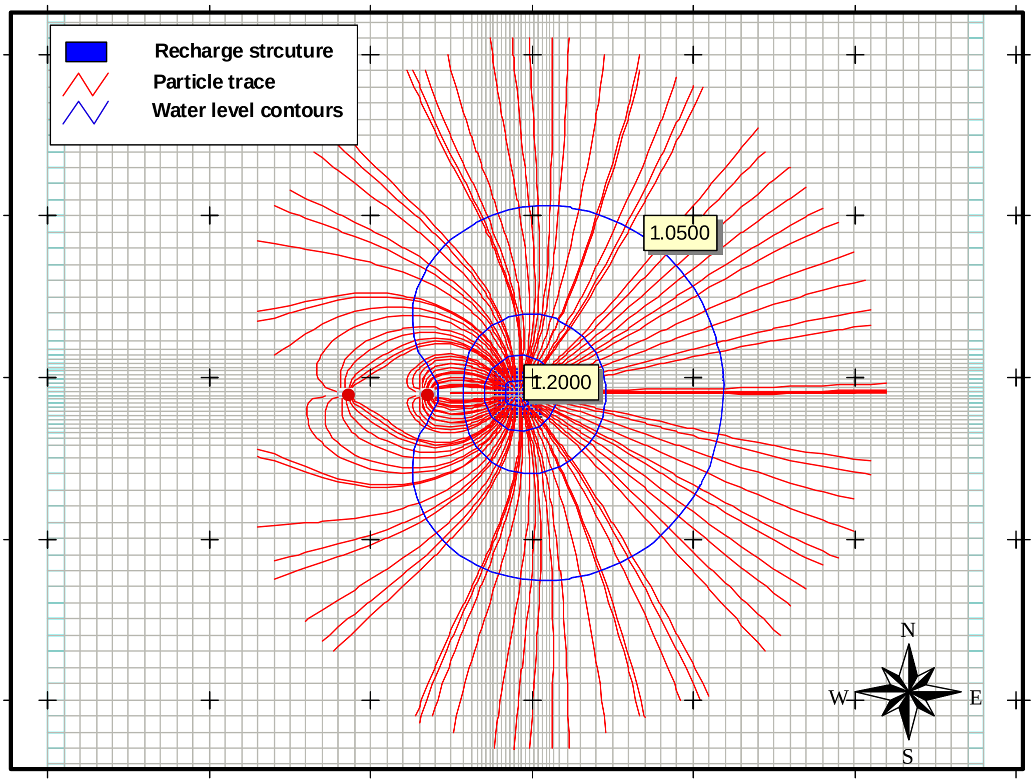

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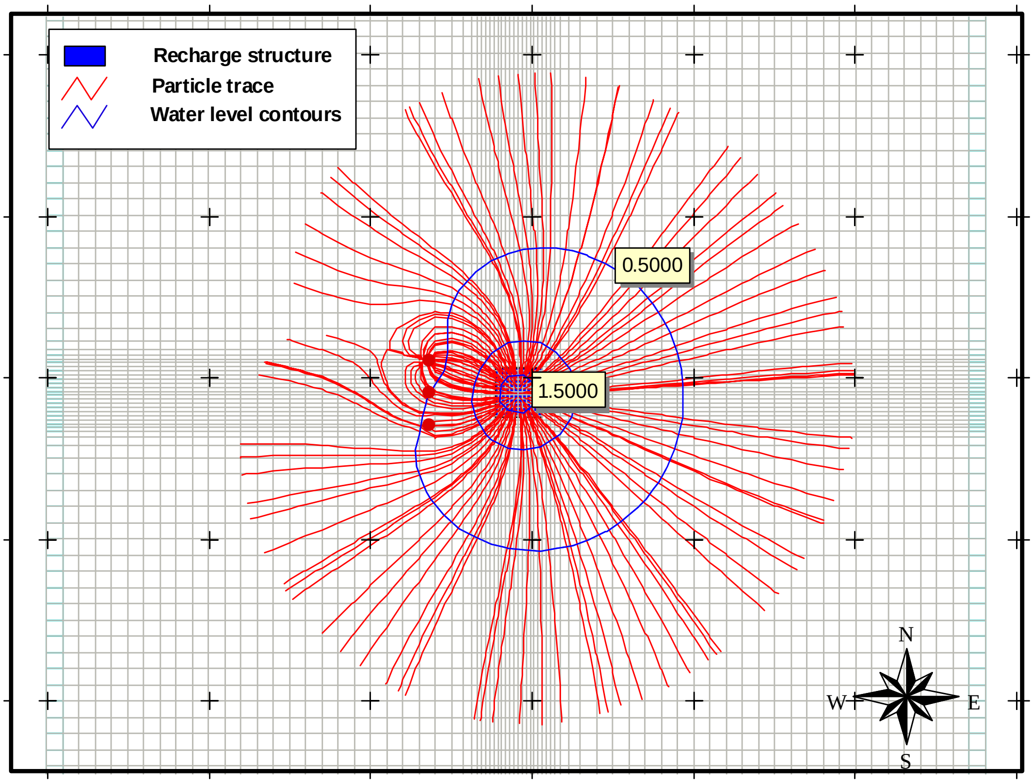

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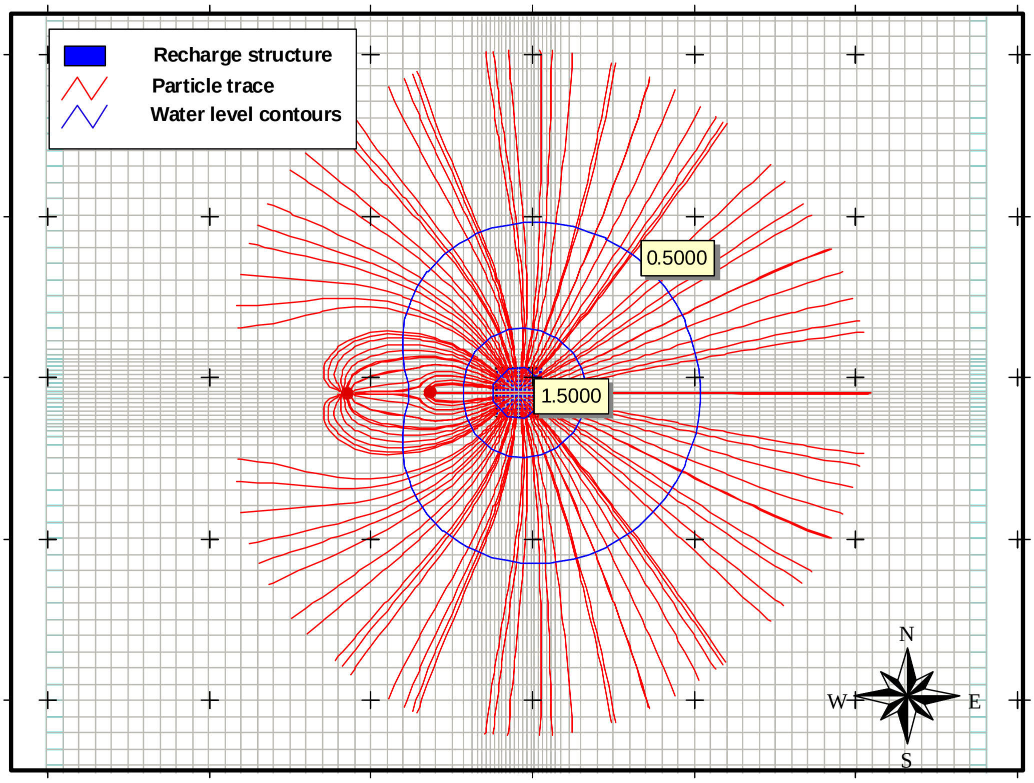

TW-Sc16

Appendix 2 Analytical spreadsheet model

The Excel spreadsheet model developed by John Barker (Barker, 1995, unpublished) can be used as a tool to investigate the impacts of recharge to a homogeneous aquifer, determining water level rises and volumes respectively.

The following input parameters need to be specified:

R1	Radius of recharge structure	L
R2	Boundary of the aquifer	L
Boundary type	0 = infinitive, 1= no-flow	
Tran	Transmissivity of aquifer	L^2/T
Stor	Storativity of aquifer	-
Qins	Artificial recharge rate for the period T0s(i-1) to T0s(i)	L/T
Rech	Natural recharge	L/T
T0s	Time of end of period of recharge i	T

Parameters are entered into the spreadsheet as shown in Figure 1. Figure 1 gives an example for parameterisation of an infinite aquifer, which is being recharged by a recharge structure of 30 m radius for 30.4 days (1 month), applying a constant recharge rate of 50 mm/d (-0.05 m/d). No natural recharge occurs and the change in water level is a function of recharge from the recharge structure only.

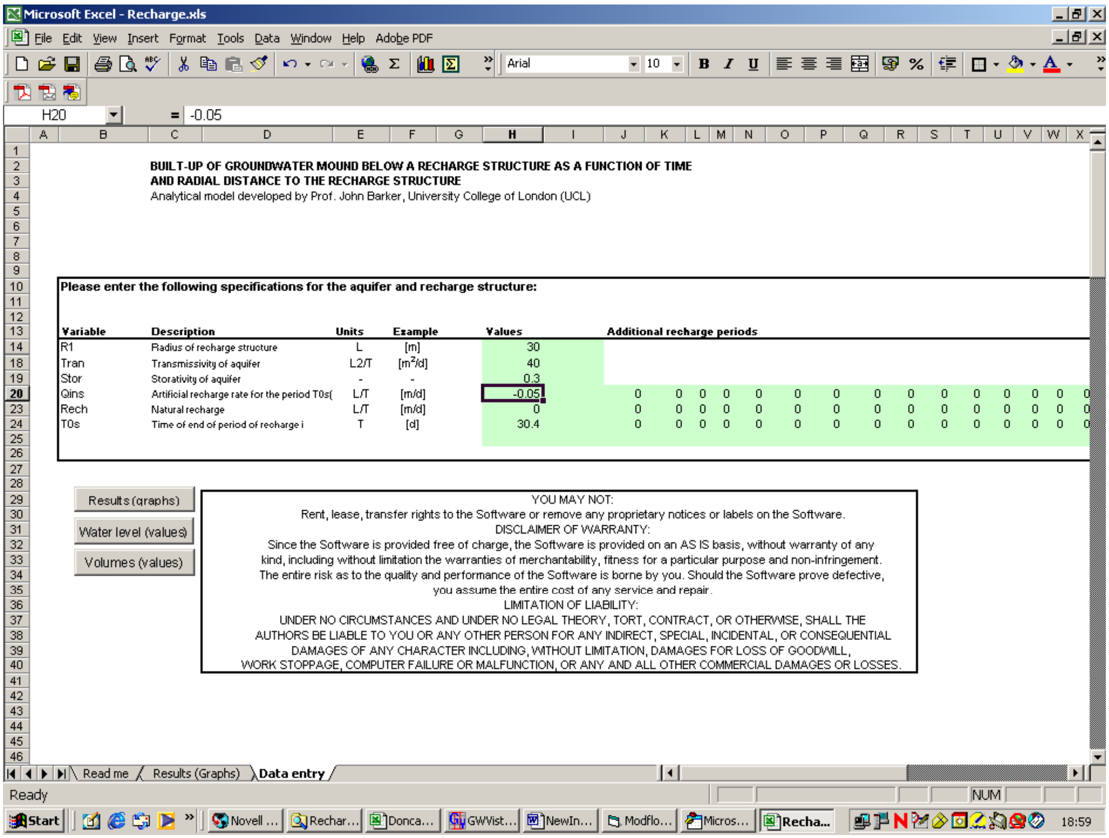

Figure 1 Data input into the spreadsheet model

If required, additional recharge periods can be entered in the model. An example is given in the table below for two recharge periods of one month duration, separated by a one month dry period:

Please enter the following specifications for the aquifer and recharge structure:

Variable	Description	Units	Example	Values	Additional recharge periods					
R1	Radius of recharge structure	L	[m]	30						
Boundary condition	Infinity=0, no_flow=2	-		0						
R2	Distance to boundary	L		500						
Tran	Transmissivity of aquifer	L2/T	[m2/d]	40						
Stor	Storativity of aquifer	-	-	0.05						
Qins	Artificial recharge rate for the period T0s(i-1) to T0s(i)	L/T	[m/d]	-0.05	0	-0.05	0	0	0	0
Qouts		L/T		0	0	0	0	0	0	0
Qbounds		L2/T		0	0	0	0	0	0	0
Rech	Natural recharge	L/T	[m/d]	0	0	0	0	0	0	0
T0s	Time of end of period of recharge i	T	[d]	30.4	60.8	91.2	0	0	0	0

After data entry, the model calculates water levels at a given distance from the centre of the recharge structure. The calculated volumes are the net gain of volume over the area out from the recharge structure to a specified radius, over a given time period. Results are given in form of water levels and volumes at specified times and distances from the structure as well as in form of graphs. Figure 2 shows the graphed output of the model for the example input values given in Figure 1.

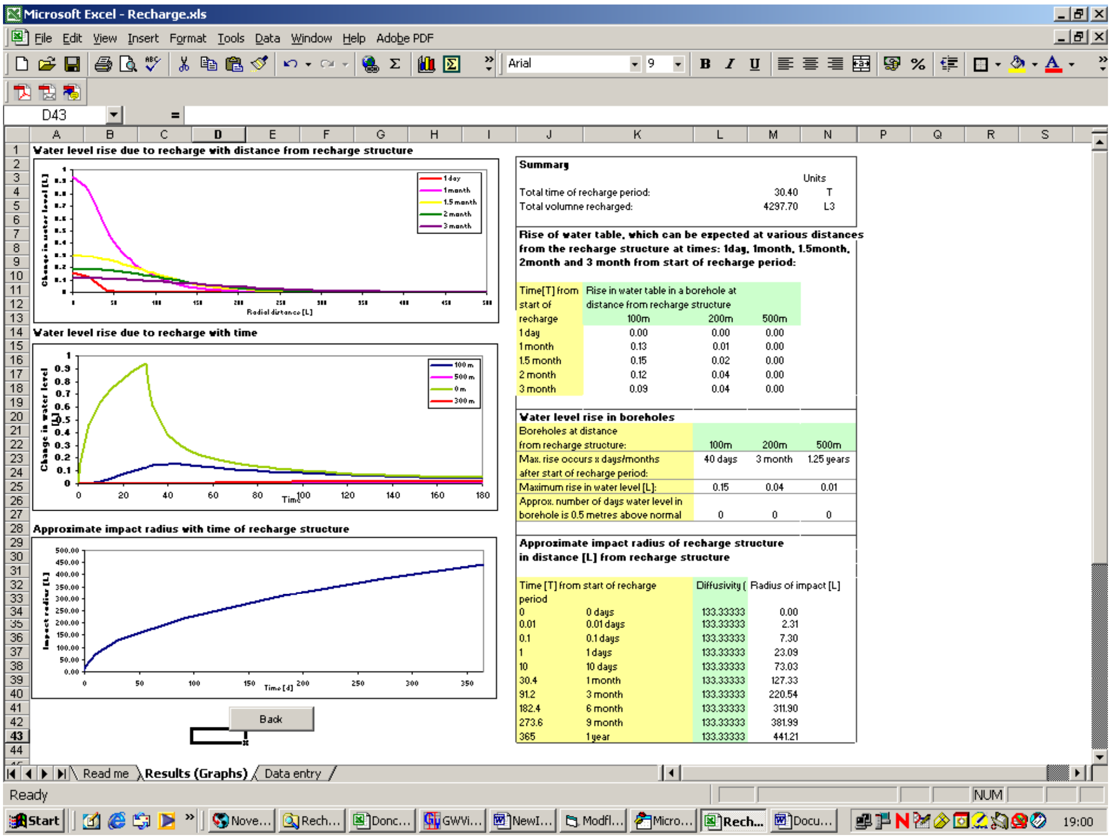

Figure 2 Analytical model output

The output includes graphs showing water level changes with distance from the recharge structure as well as with time. Also approximations are given on expected water levels in boreholes at various distances from the structure for different times. Peak water levels at specified distances from the structure are given, as well as an approximation on how long water levels remain above a specified water level height.

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