Saph Pani

Enhancement of natural water systems and treatment methods for safe and sustainable water supply in India

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Preliminary models and system design

SAPHPANI

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1 Chennai

1.1 Site specific background knowledge

1.1.1 Synthetic site description

Chennai is the largest city in South India located in the eastern coastal plains. Water supply to the Chennai city is met by reservoirs and by groundwater. Most of the groundwater is pumped to the city from the well fields located in the Araniyar and Korttalaiyar River (A-K River) catchment north of Chennai (Figure 1). The total surface water area of the A-K River catchment is around 6282 km^2, divided between Andhra Pradesh and Tamil Nadu. Severe pumping from these regions for supply to the Chennai city and for local irrigational needs has also resulted in seawater intrusion. The Minjur well field lies nearest to the coast (9 km) and it is hydraulically connected with the sea. This well field has been intruded by seawater up to a distance of 15 km since 1969 due to extensive extraction of groundwater for agricultural, industrial and domestic uses for prolonged periods. The average rainfall on the basin is 7-9 billion m3 /year, which corresponds to 950-1250 mm/year. Even though the annual rainfall is moderate, extreme cases of very high daily rainfall were recorded in past in the Chennai basin. Severe rainfall during short periods of time combined with high percentage of impervious areas in this region is the major source of flooding. Thus, the Chennai region on one hand is affected by floods and on the other by severe shortage of water.

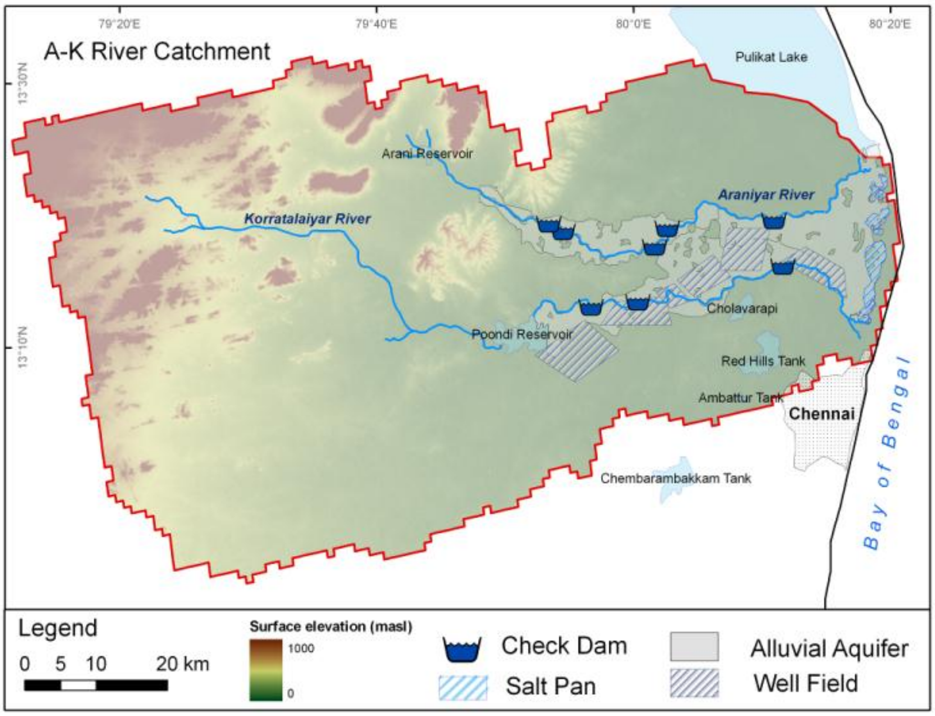

Figure 1 Overview of A-K River catchment

The north east (winter) monsoon is the more significant, as it replenishes the surface reservoirs and also recharges the groundwater. Water is stored in reservoirs and used cautiously. They are virtually empty before the next annual rainfall. The shortfall in surface water storage systems is met from groundwater resources. About one third of the water demand is met by groundwater from several well fields about 30 km north of Chennai.

The city has two major rivers namely Adyar and Cooum. Both these rivers usually carry sewage and only heavy rain events can get these rivers flushed. The city itself has very meagre groundwater resources due to very little rainfall recharge. Most of the inner basin surface water comes from three reservoirs, namely Redhills, Poondi and Cholavaram. Maximum storage capacity of these three reservoirs is around 210 Mm^3. The storage capacity from these three reservoirs would last only for half a year. The inter basin transfer consists of Veeranam lake (235 km away) and Kandaleru dam (175 km away) and groundwater is abstracted from the well fields north and north west of Chennai. The water supplied by Chennai Metro Supply and Sewage Board does not cover the demand and the accumulated gap is at the end of a year around 200 Mm^3 (20 %). This gap is met by private groundwater abstraction and by the commercial water companies.

The main objectives for the case study site in Chennai is to undertake a comprehensive assessment of MAR for coping with sea-water intrusion and groundwater overexploitation and to develop recommendations and a management plan for implementing MAR systems in Chennai that utilize excess monsoon water to counteract seawater intrusion,

1.1.2 Previous projects

Balakrishnan (2008) investigated the hydrogeology and hydrochemistry of the Chennai region. The author identified salinity ingress as one of the main groundwater related problems in the region.

Ganesan and Thayumanavan (2009) developed a 3D MODFLOW/MT3D flow and transport model for the coastal aquifer north/northeast of Chennai. The model was calibrated by monthly average inflows, outflows and piezometric head contours for the period from 1976 – 82 and simulated the movement of saltwater for the period from 1983 – 96. The calibrated model was used for seven scenarios with various groundwater abstraction rates and injection rates for the period from 1997 – 2020. According to the authors, the fresh-saltwater interface, expressed as the 1000 mg/L isoline, will be under a worst case scenario approximately 11 km from the coast. Reduction in groundwater withdrawals and/or the injection of freshwater was found to reduce the seawater movement toward the land. The model does not account for density dependent flow and the hydraulic heads used for calibration were temporally and spatially averaged. However, the optimal pumping and injection rates stated in this study may provide useful information for an improved and extended numerical model.

Sundaram et al. (2008) investigated the vulnerability of the coastal aquifers in Pondicherry (approx. 120 km south of Chennai) in terms of seawater intrusion using GIS methods and evaluated the effects of MAR techniques on the dynamics of the freshwater-seawater interface in the region. Runoff potential was calculated by Soil Conservation Service from the US department of agriculture along with curve number tables. The effect of MAR on seawater intrusion was evaluated using groundwater flow rate equation from Raudkivi & Callander (1976). The authors found out that the runoff potential in the region is sufficient for MAR to counteract seawater intrusion.

Anuthaman (2009) studied the groundwater augmentation by flood mitigation in Chennai region using HEC HMS and HEC RAS. Elango (1992) carried out a hydrogeochemical study and mass balance modelling of multilayered aquifers in Chennai region.

1.1.3 Existing models

Anuthaman (2009) used HEC HMS and HEC RAS which are freely available software to study groundwater augmentation by flood mitigation in Chennai region. The river basins of Adayar, Coovum, Kosasthalayiar and Araniar were delineated using the HEC-Geo RAS and ARC VIEW software packages. The river flood flows and its attenuation were analyzed by using HECHMS software. The flood flows were classified as channel flows and bank full flow condition. The flood flow is attenuated for use as recharge to groundwater. The application of a mathematical model to analyze the regional groundwater flow considering entire study area as a single entity with the four rivers acting as recharge boundaries was carried out. The Visual Modflow package was used to estimate the mass balance of this groundwater basin applied for two conditions of with and without recharge by flood attenuation. Thus the quantifying of the groundwater basin resources with a mathematical model was completed. The drainage basin concept application to the study area was achieved by determining the flood wave propagation by the rivers and its classification as dynamic, kinematic and diffusion waves.

Elango (1992) carried out hydrogeochemical study and mass balance modelling of multilayered aquifers in Chennai region. A mass balance discrete model of the system was built up for this area by subdividing the formation into three zones as soil, upper aquifer and lower aquifer zones. By applying conservation of mass to each box, and specifying the appropriate rules and reactions, the movements of solutes along with water are simulated. The geochemical reactions identified such as dissolution and deposition of mineral and ion exchange reactions are solved by Newton's interactive technique to determine the new concentrations. The model developed was coded in Fortran 77. The model predicted that during initial recharge, the evaporation concentrated soil water was flushed in and thus groundwater concentration increased with rise in water level. As the recharge continues all the concentrated water and deposited salts were flushed in and only fresh rainwater recharges the aquifer. The model utility was demonstrated by a hundred years run to understand the behaviour of the aquifer system in various conditions.

1.2 Models to be developed

1.2.1 Objectives of Saph Pani modelling work

Overall objective of the Chennai study in SAPH PANI is the development of technical recommendations for implementing MAR systems in Chennai that utilize excess monsoon water to counteract seawater intrusion

The basic objective of the catchment scale model is to analyse the water balance in the catchments of the rivers Korratalaiyar and Araniyar. The water balance should include all in- and outflow rates being;

Inflow:

1) Rainfall and Runoff
2) Groundwater inflow
3) Sea water inflow
4) (waste water inlets)

Outflow:

1) Extractions
5) Groundwater outflow
6) Sea water outflow
2) Evaporation

Groundwater interaction strongly depends on the groundwater extraction in the region (s. well field in Figure 1) and the potential recharge of the available checkdams. A detailed hydronumerical and hydrogeological model can quantify this. Such a coupled model should be able to describe all the components listed above and can be calibrated on:

- Observed groundwater levels
- Observed surface water levels, especially within the reservoirs
- Seasonal dynamics can be calibrated according to rainfall events, which have been observed in detail.

From the present state water balance analyses, potential measures to counteract sea water intrusion can be derived. The effect of such measures can then be analysed with the model. It should therefore be guaranteed that the model is able to implement these measures in an accurate way.

Pilot site scale model

- quantification of infiltration rates and characterisation of surface-groundwater interactions at specific site(s)
- understanding the main geochemical processes during infiltration of fresh water into an brackish/saline aquifer (sorption, ion exchange, dissolution etc.)

1.2.2 Target groups, potential endusers of SAPH PANI models

Experts only

1.2.3 Modeling tools to be used

The catchment scale model will contain three components:

1) a Rainfall-Runoff model to describe the rain fed inflow into the surface water system as well as the infiltration into the subsoil. This model will be built at the scale of the whole catchment. A special NAM-based Rainfall Runoff module of MIKE11 is intended to be set up. This module is automatically coupled to MIKE11 (s. below).
2) A 1D surface water model with MIKE11 will be set up. This module can calculate looped networks and is able to describe regulated structures (a possible measure in regard to check dams). Also reservoirs can be easily implemented, including area dependent rainfall and evaporation. The inflow of the rainfall runoff module is automatically being set as an additional boundary in the model. The downstream sea water level can be set dynamically if needed and surface water extractions can be taken into account. MIKE11 can be easily connected to FEFLOW (s. next point), including transport processes (salinity). The surface water model will include at least the rivers Korratalaiyar and Araniyar, but if needed it can be extended with the most important tributaries.
3) A 3D FEFLOW model will describe the subsoil processes. It is able to describe density dependent processes and can be coupled to MIKE11 to describe the interaction between the ground- and surface water in detail. The FEFLOW model will probably be restricted to the alluvial aquifer.

The refined flow and transport model will examine the surface/groundwater interactions on pilot site scale. Target: Development of 2D/3D transient flow and transport model, calibration with hydraulic heads and environmental tracers i.e. temperature, chloride, bromide, stable isotopes etc. Software: MODFLOW, SEAWAT or VS2DI

1.3 Modeling tasks and responsible partners

Anna University (AU), DHI/WASY and Freie Universitaet Berlin (FUB) will work together to meet the above mentioned goals in a spirit of partnership among equals. Nevertheless, the main responsibilities can be summarized as follows:

- Primary data generation as an input for the model(s) will be organized and carried out by AU and FUB
- Development of the catchment scale model (AU, DHI/WASY)
- Development of pilot scale model (FUB)

1.4 Conceptual Model of the study site

The conceptual model (area of 1575 km^2) is framed from a detailed study of the geology, borehole lithology and water level fluctuations in wells. In the coastal side up to 25 km the triangular mesh was generated with a length of 100m. The elements are progressively made coarser towards the west, where the length of the mesh is 400 m (Figure 2). The thickness of the aquifer is decided based on the lithological cross section. This area has an aquifer thickness of 50 m, which is divided into 3 layers. Boundary conditions were assigned based on the groundwater flow from the nearest cells. The eastern part which is bounded by the Bay of Bengal is considered as a constant head boundary. The northern and southern boundaries are assigned no flow condition. The western and southwestern side boundary is considered variable head which is based on the river flow. Initial conditions of hydraulic head are taken from March 1996 groundwater level (Figure 3).

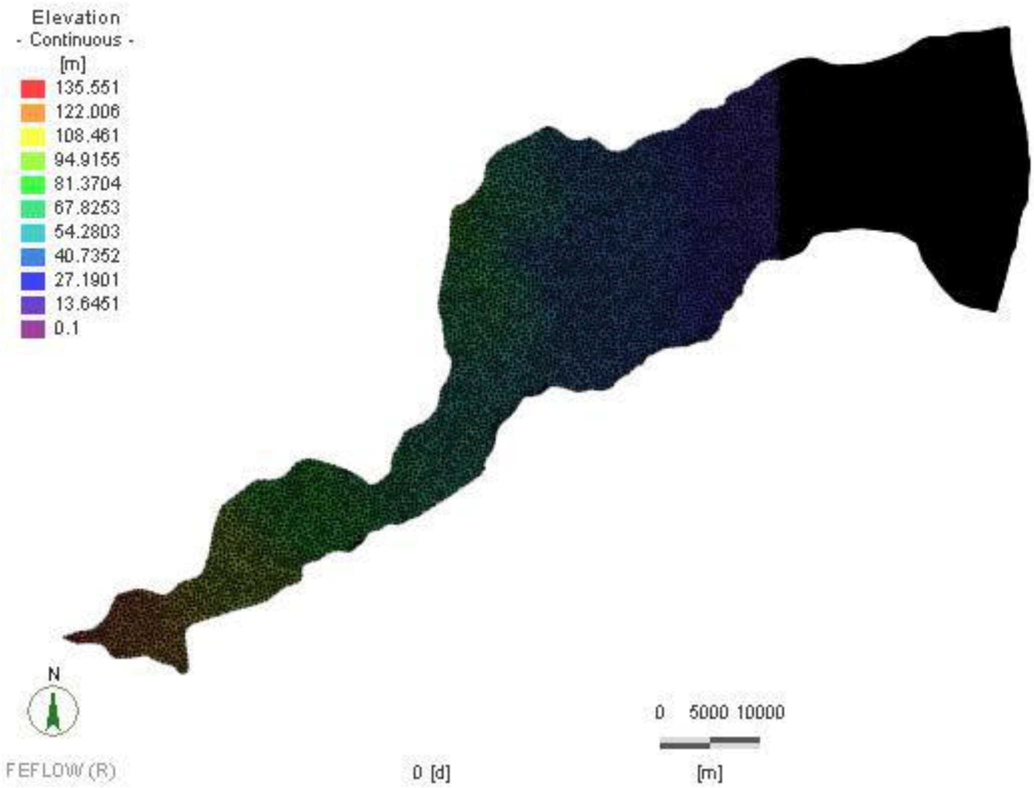

Figure 2 Discretization of the model area with ground elevation

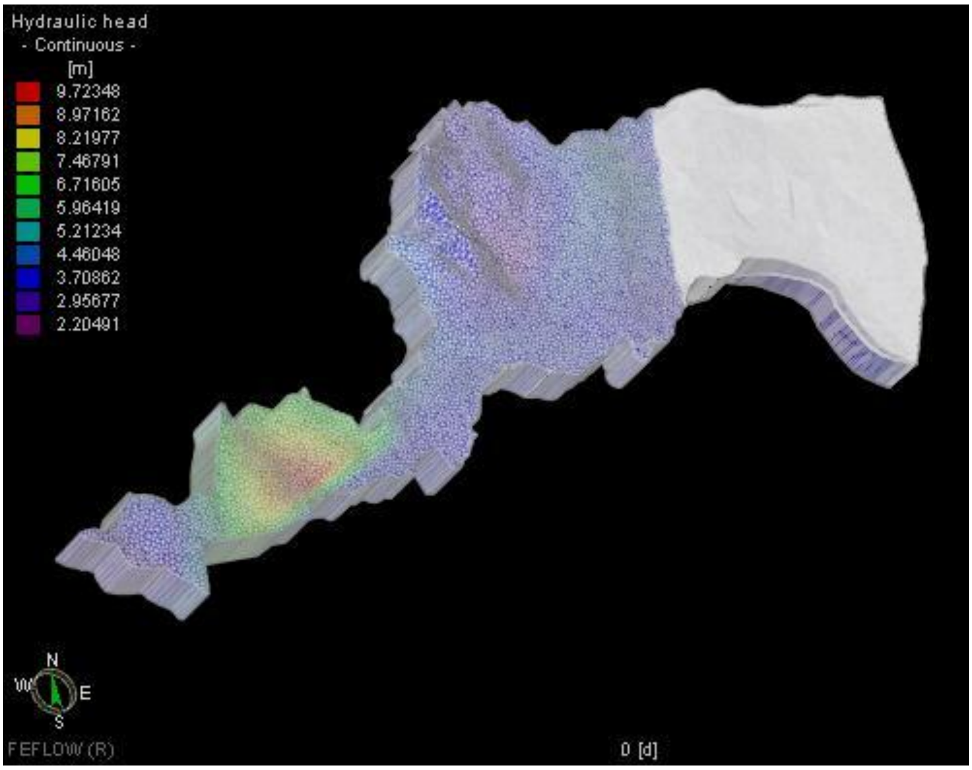

Figure 3 Initial groundwater level during March 1996

The conceptual and numerical model for surface water flow was established in the framework of a thesis (Punit Kumar Bhola, 2012). After a thorough study of the A-K Basin, drainage network and morphometric analysis was performed and the study reveals that the drainage area of the basin is passing through an early mature stage to old age stage of the fluvial geomorphic cycle. The growth of the stream segments in the basin area is relatively affected by rainfall. Bifurcation ratios (between 3.97 and 4.8) show that the drainage network within the study area is in a well-developed stage. The drainage basin size analysis reveals that the flooding risks might be relatively low. Peak discharge at the river outlet was estimated for various stream velocities using GIUH techniques and subjected to calibration. A comparison with NAM model results suggests a stream velocity of 0.5 m/sec, providing a reasonable match for both River Araniyar and River Korttalaiyar.

A functioning hydrological model for the river Araniyar and Korttalaiyar has been developed with the MIKE 11 RR module. A two-stage model has been designed to examine flood flow with the ability to couple to a suitable groundwater model later in the overall project. In the first stage, a NAM based hydrological model was constructed from 8 years of available daily discharge data from Poondi reservoir. Since the model was calibrated for an 8 year time period, this covers a wide range of hydrologic and climate conditions, which gives confidence in the model's ability to predict streamflow conditions under a variety of scenarios. The model gives a satisfactory comparison with observed flow records with a R2 value of 0.6. Main focus was given to achieve least volume and peak errors. The model over-predicts the total volume in 8 years by 10.5% and almost 7%

of peak error for a discharge greater than 300 m^3s^{-1}. However, it has been observed that the model over-predicts the volume of flow in case of heavy rainfall. The results also indicate that the model fails to predict low flow very well because of a high surface and root zone storage coefficients. Nevertheless, in respect to the relatively low quality of available input data, the model can be used to create boundary conditions for the MIKE 11 HD model. Also, a possible optimization of the model in a later stage can be achieved in a convenient way.

1.5 Status of numerical modelling at M12

In a second stage, the obtained model parameters were extended homogenously in entire A-K basin and a spatial distributed rainfall estimated from 8 stations in the basin was used as input rainfall to the model subcatchments. The complete model, compromising the models of stage 1 and 2 could then be coupled with the MIKE 11 HD model (Punit Kumar Bhola, 2012).

The MIKE 11 HD model consists of two main rivers (Araniyar and Korttalaiyar) and various checkdams along the river courses. The model has been tested successfully on numerical stabilities and describes all the basic functionality e.g. the effect of integrated structures, diversions and reservoirs in a realistic way. Currently there are some limitations related to the cross-section data including the elevation accuracy, especially at structures along the river, to the length of cross-sections beyond the river bank and to the general coverage of cross-section data, particularly at the canal leading to Cholavaram reservoir in river Korttalaiyar. Additional field surveys or data collection may be needed to verify the operation of gates for the diversion of water. Furthermore, abstraction (for irrigation and drinking supply) and waste water inflow need to be defined to complete the assessment of a general water balance in the system in a later stage of the overall project. The predictive capabilities of the current model are limited by several assumptions and lack of data. Involvement of local Indian authorities and DHI-WASY experts in redefining the model boundaries and system might rectify the errors introduced by these assumptions. Important features include obtaining a finer resolution Digital Elevation Model, improvement of the bathymetry of the rivers and installing more gauging stations in the A-K basin (especially upstream rainfall stations and discharge stations at important anicuts and junctions).

The next step in the overall project is to set up a 3-D FEFLOW groundwater flow model, capable to describe density dependent processes. This model will then be coupled to a calibrated MIKE 11 river model to describe the interaction between the ground- and surface water in detail.

1.6 Site-specific literature list

1.6.1 Publications (journals, conferences….)

Balakrishnan , T. (2008) DISTRICT GROUNDWATER BROCHURE CHENNAI DISTRICT, TAMIL NADU , Government of India , Ministry of Water Resources , Central Ground Water Board , South Eastern Coastal Region ,

Ganesan , M., Thayumanavan, S. (2009) Management Strategies for a Seawater Intruded Aquifer System , Journal of Sustainable development, Vol. 2, No 1

Sundaram, Dinesh, G.., Ravikumar and D.Govindarajalu (2008), Vulnerability assessment of seawater intrusion and effect of artificial recharge in Pondicherry coastal region using GIS, Indian Journal of Science and Technology, Vol. 1, No. 7, 1-7

Raudkivi AJ and Callander RA (1976) Analysis of ground water flow. Edward Arnold (Publishers) ltd, Old Woking, Surrey, London.

Sathish, S. and Elango, L. (2011) Groundwater quality and vulnerability mapping of an unconfined coastal aquifer. Journal of Spatial Hydrology, Vol. 11(1), 18-33.

Sathish, S., Elango, L., Rajesh, R., and Sarma V.S. (2011) Application of Three Dimensional Electrical Resistivity Tomography to Identify Seawater Intrusion, Earth Science India, Vol. 4(1), 21-28.

Sathish, S., Elango, L., Rajesh, R., and Sarma V.S. (2011) Assessment of seawater mixing in a coastal aquifer by high resolution electrical resistivity tomography. International Journal of Environmental Science and Technology, 8 (3), 483-492.

Senthilkumar, M. and Elango, L. (2011) Modelling the impact of a subsurface barrier on groundwater flow in the lower Palar River basin, southern India. Hydrogeology Journal, 19(4), 917-928.

Sivakumar C. and Elango, L. (2010) Application of solute transport modeling to study tsunami induced aquifer salinity in India. Journal of Environmental Informatics, 15(1), 33-41.

Elango, L. and Manickam, S.(1987) Hydrogeochemistry of the Madras aquifer, India - Spatial and temporal variation in chemical quality of groundwater. Geol.Soc. of Hong Kong Bull. No. 3, pp. 525-534.

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Elango, L. and Ramachandran, S. (1991) Major ion correlations in groundwater of a coastal aquifer. J. Indian Water Reso. Soc., 11: 54-57.

Gnanasundar. D and Elango. L (1998), Groundwater quality of a coastal urban aquifer, Journal of Environmental Protection, Vol.18, pp. 752-757.

Gnanasundar. D and Elango. L (1999) Groundwater quality assessment of a coastal aquifer using geoelectrical techniques, International Journal on Environmental Hydrology, Vol. 6, pp 21-33.

Gnanasundar.D and Elango.L (2000) Groundwater Flow modeling of a coastal aquifer near Chennai City, India, Joul. of Indian Water Reso. Soc., Vol. 20, 4/162-171.

Senthil Kumar, M., Gnanasundar, D. and Elango,L.(2001) Geophysical studies in determining hydraulic characteristics of an alluvial aquifer, Journal of Environmental Hydrology, Vol.15/9, pp. 1-8.

Punit Kumar Bhola (2012): Modelling of Ungauged Araniyar–Korttalaiyar River Basin, Chennai, India. Master Thesis, Brandenburg University of Technology, Cottbus

1.6.2 Other accessible data (web, reports…)

http://www.chennaimetrowater.tn.nic.in/public/lake.htm

daily lake level data from the reservoirs

daily rainfall measurements

2 Delhi site

2.1 Site specific background knowledge

2.1.1 Synthetic site description

Transport and transformation processes of Nitrogen species are studied in an urban aquifer in New Delhi (India). The study site is located close to the Oklah barrage in the south eastern part of New Delhi (Figure 4). Here, the Yamuna River is heavily polluted by poorly treated and untreated urban waste water and the existing drinking water production wells close to the river produce bank filtrate of low quality. The high concentration of nitrogen (mostly ammonia) makes the abstracted groundwater unfit for drinking water purposes and most of the production wells are abandoned. Nonetheless, the groundwater is used by urban dwellers and small scale farmers. Before distribution, the bank filtrate is treated for nitrification, in order to oxidize the ammonium present. The current plant is designed to treat 4 mg/L of ammonium – however, it is predicted that in future up to 10 mg/L of ammonium are likely to occur. Different options to sustain drinking water quality are to be evaluated in WP1 such as improving source water or enhancing the extensive post-treatment.

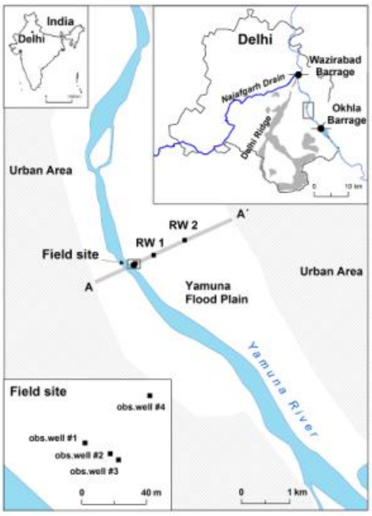

Figure 4 Location of field site during the TECHNEAU project. RW = Ranney Well, horizontal filter well

WP5 activities focuse on the transport behaviour of nitrogen species under the given environmental conditions. Column experiments will be used to evaluate transformation and transport processes of nitrogen under changing redox conditions. Specific cation exchange capacity, organic carbon content and other sediment properties (grain size distribution, effective porosity) will be determined. Based on the column experiments, various abstraction schemes and prediction of changes in redox conditions and the resulting ammonium and nitrate concentrations in pumped water in NCT Delhi will be evaluated. Already existing numerical models (2D, flow and transport) will be further developed in order to verify and predict nitrogen fate and transport. The reaction network will be established after the identification of the main geochemical reaction such as anammox, nitrification, denitrification, redox reactions (Figure 5). Based on the available data, a 1D model will be developed. The calibrated and validated model will demonstrate the likely effect of different remediation strategies on groundwater quality. Different abstraction schemes or the improvement of river water quality will be tested during scenario modelling.

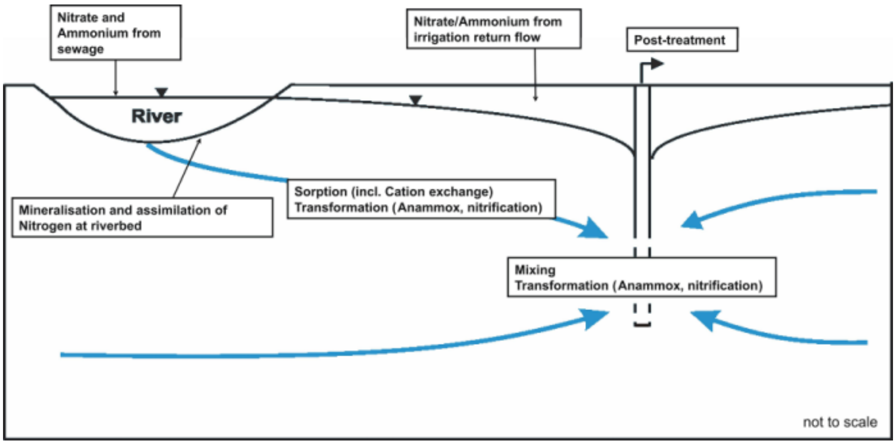

Figure 5 Sketch of main geochemical processes of N-species during anoxic subsurface passage.

2.1.2 Previous projects

Project acronym/name: TECHNEAU

Duration: from 2006 to 2010

Framework: FP6

Coordination/partnership : Partner

What was done: At the central Delhi field site the impact of highly contaminated surface water infiltration on the urban aquifer systems was investigated. At this field site, RBF takes place because of dominant losing river conditions due to large groundwater abstraction. Fluctuations of the hydraulic head in combination with a conservative tracer (chloride) and a retarded tracer (heat) were measured, evaluated and modelled to determine (i) infiltration rates and (ii) groundwater travel times, (iii) to perform a sensitivity analysis and (iv) to calculate a water budget for the flood plain aquifer.

Website or information on the web : www.techneau.org

2.1.3 Existing models

A vertical two-dimensional (2D) transient groundwater flow model was constructed using Modflow, and transport was modelled with MT3DMS under the graphical user interface of Visual Modflow. The model accounts for infiltration into and processes in the saturated zone, but does not simulate surface runoff and percolation through the unsaturated zone. The model was calibrated with hydraulic heads and tracer curves of chloride and temperature. Prior to the transport modelling with MT3DMS, ModPath was used to visualize groundwater flow directions and pure advective travel times. The simulation time from November 2006 to March 2008 was divided into 45 stress periods, each of ten-day duration. Each stress period was attributed to the corresponding hydraulic head and input for solute transport (chloride and temperature) at the river boundary. A steady-state model provided the initial hydraulic heads for the following transient simulations. The model area extends over a length of 2400 m on the eastern side of the Yamuna River in the central part of Delhi. The grid was oriented so that the flow is parallel to the x-axis. The model domain was divided into 100 m wide columns and 1 m layer thickness. Near the observation wells, the grid was refined to columns of 1 m width, resulting in 55 columns and 20 layers in total. In total, the model represents 50 m depth of constant layer thickness (Figure 6). The bottom of the model domain corresponds to the hardrock unit and was attributed to a no-flow boundary.

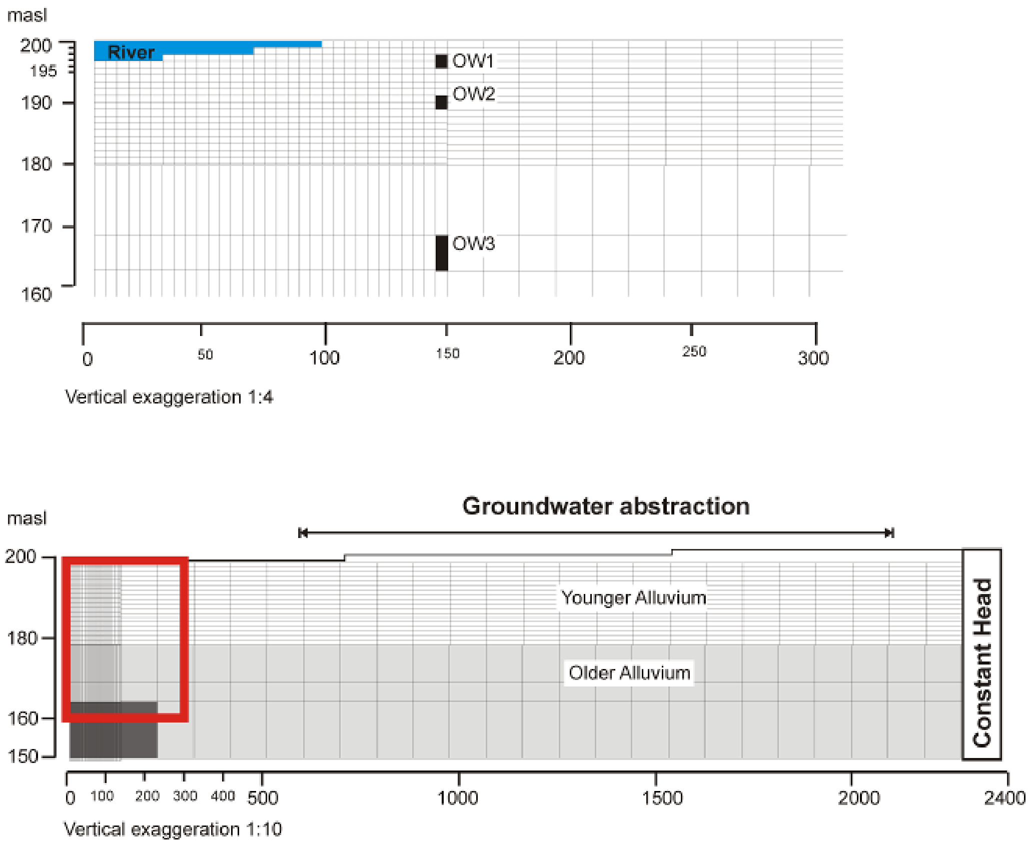

Figure 6 Grid discretization and boundary conditions.

Chloride was used as a tracer substance to evaluate travel times at the SW/GW interface because it is highly mobile and conservative in its chemical behaviour. Travel time of bank filtrate was determined by comparing the seasonal signal in the Yamuna River with the shifted and attenuated signal in the observation wells (Figure 7).

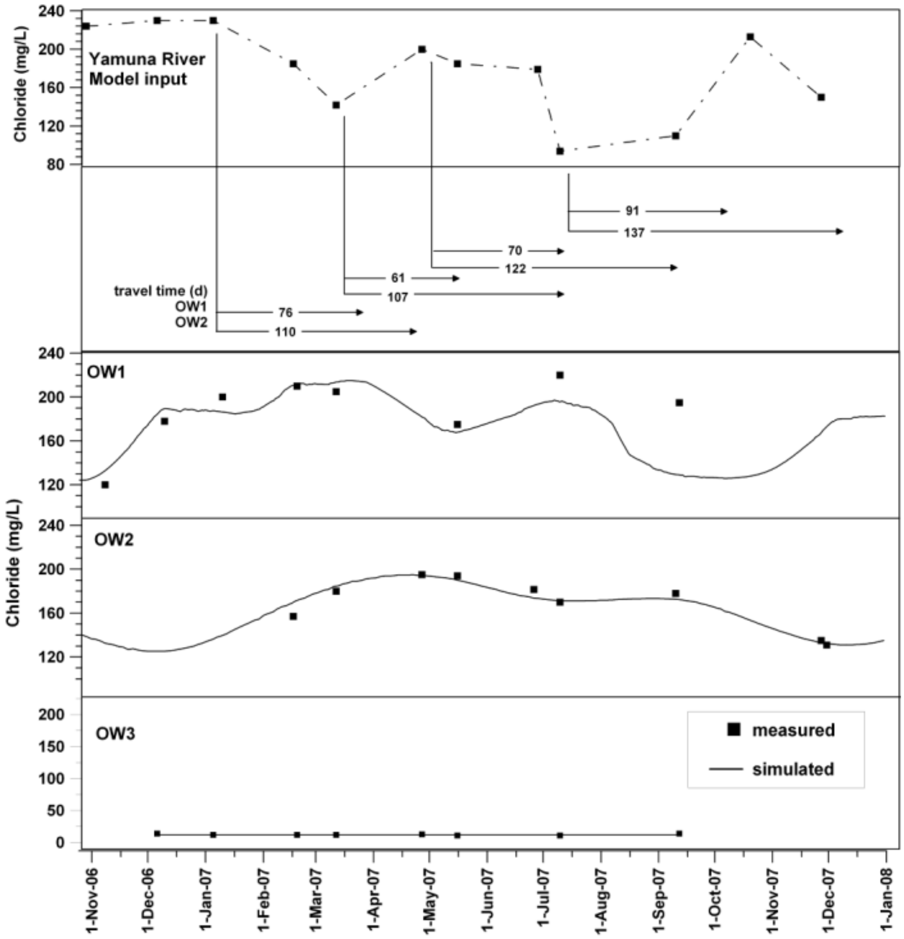

Figure 7 Measured chloride (square) with the calculated curves (line) in the shallow (#1), medium (#2) and deep observation wells (#3) in combination with the Yamuna River. The bars at the top show the precipitation values in Delhi to indicate dilution effects during rainy periods

2.2 Models to be developed

2.2.1 Objectives of Saph Pani modelling work

The aim is to identify the controlling geochemical processes of nitrogen fate and transport during subsurface passage. Ammonium movement can be retarded by physicochemical processes such as sorption (including cation exchange), or biological processes such as microbially induced transformations, depending on aquifer geochemistry and the nature of the groundwater flow system. Isotopic measurements of water and relevant nitrogen species will contribute to a better understanding of transport and transformation processes. On the basis of an updated and improved reactive transport model a quantification of the reaction rates and process understanding is intended to be achieved. Scenario calculations will evaluate remediation options such as improved source water quality, in-situ remediation, adapted well operation and enhanced extensive post-treatment. Interpretations of field site data in combination with column experiments will result in remediation guidelines.

2.2.2 Target groups, potential endusers of SAPH PANI models

Experts

2.2.3 Model type

Time scale, steady-state or transient state: steady-state and/or transient

Spatial scale: -

FE, FD, nesting…: FD

1D-3D: 1D

Flow and transport: both

(Geo)chemical model, reactive flow: geochemical

2.2.4 Modeling tools to be used

Tools for data management: MSAccess, ArcGIS

Tools for modelling: Modflow, MT3DMS, PHT3D

2.2.5 Modeling tasks and responsible partners

KWB - PhD Maike Gröschke (data collection, model construction), Dr. Gesche Grützmacher (supervision)

FUB (Dr Christoph Sprenger (data collection, supervision on site), Prof. Michael Schneider (supervision)

2.3 Conceptual Model of the study site

Based on data from the Techneau project a conceptual redox zonation was developed for the field site in Delhi.

Hydrogeology

At the field site, three lithological units were encountered: (i) the recent alluvial (ii) the older alluvial (iii) the quartzitic hardrock. The recent alluvium is composed of Holocene sediments of the Yamuna floodplain, deposited close to the present course of the river. This unit consists mainly of grey coloured medium sand fluviatile deposits interbedded with calciferous gravel size concretion, locally known as *kankar*. The mineral assemblage consists, in the order of decreasing proportion, of Quartz, Mica (Illit) and Chlorite, accessory Kaolinite, Montmorillonite, Feldspar and Calcite. The upper aquifer extends down to 12 m below ground level at the river and increasing thickness to the east was observed (up to 30 to 40 m below ground level). The coefficient of hydraulic conductivity (k-value), estimated by various pumping tests, is in the order of 4×10^{-4} m/s. The upper sediments have been deposited upon a series of variable thickness of older alluvium. The older alluvium is composed of tertiary sediments, which are outcropping to the west of the present course of the Yamuna. This unit consists mostly of yellowish to brown coloured silt and is more consolidated than the upper active floodplain sediments. Mica is accessory or absent and the fine sand is in places interbedded or mixed with layers of fine to medium sand. The k-value was estimated by small-scale pumping tests with 1x 10^{-5} - 1x10^{-6} m/s. At a depth of 38 m below ground level, the Precambrian metamorphic hardrock (locally known as *Aravalli* formation) was encountered. The upper part of this quartzitic unit is weathered and fractured and acts as an aquifer. The basement is, due to low permeability, considered as an aquiclude.

Classification of redox zonation at the field site

An attempt was made to characterise the redox conditions in the flood plain aquifer, based on the absence or occurrence of terminal electron acceptors. The concentration of measured terminal electron acceptors such as O_2, NO_3, Mn, Fe, SO_4^{2-}, HS^- in the flood plain aquifer and the Yamuna River are shown in Figure 8.

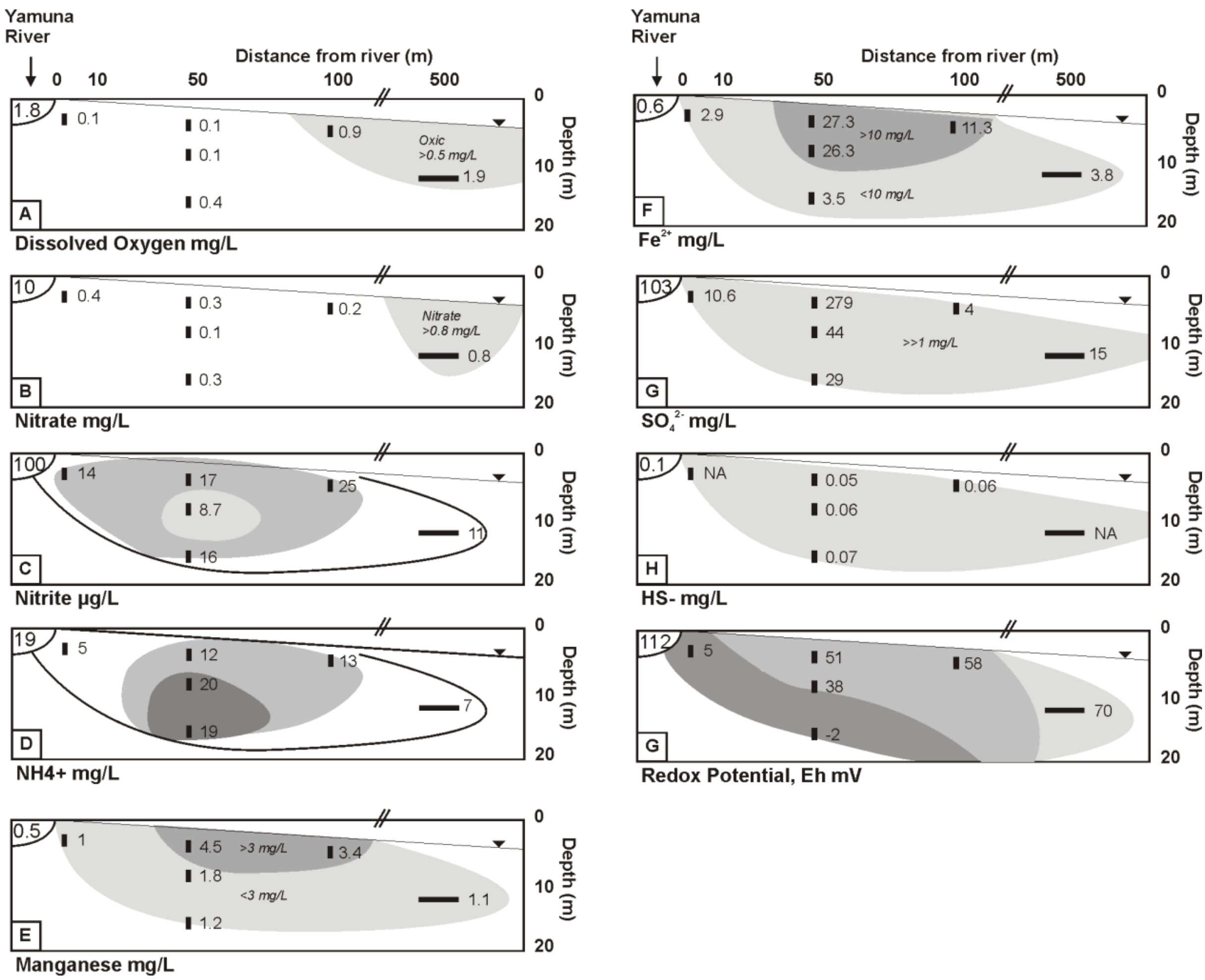

Figure 8 Cross sectional view of the distribution of main terminal electron acceptors (O_2, N-species, Mn, Fe, SO4, HS) and measured redox potential (Eh). Bars represent approximate depth and location of filter screens of sampling points.

The overall picture is an inverted redox sequence with degradation of organic matter by different electron acceptors (Figure 9). Reactive organic matter is available in abundance through the constant supply with domestic sewage. Close to the river groundwater is already sulphate reducing. It is not possible to distinguish between iron and manganese reducing zones. Most of the aquifer is characterised by Fe/Mn reducing conditions. Overlapping of redox zones is identified for the Fe/Mn reducing and the oxic/suboxic zone. Flood recharge during the monsoonal inundation period takes place only between the dike and the river. The groundwater recharge mechanisms behind the dike are irrigation return flow and direct recharge from monsoon rain. If the redox zonation is in steady-state conditions or transient conditions cannot be clarified.

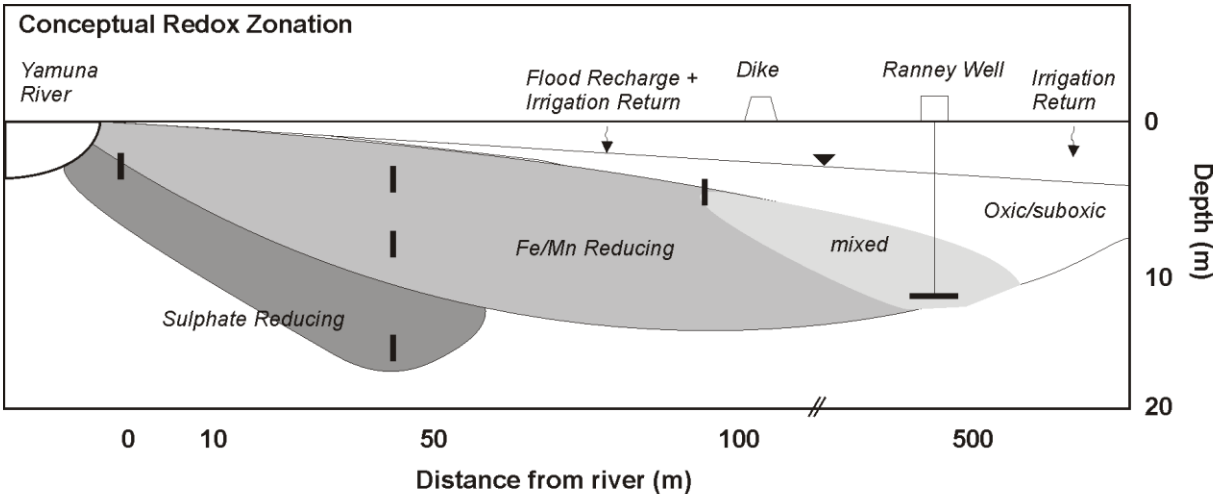

Figure 9 Conceptual redox zonation for the urban flood plain aquifer in Delhi. Bars represent approximate depth and location of filter screens of sampling points.

2.4 Status of numerical modelling at M12

The foreseen (DOW) starting date of Task 5.2 "Modelling and optimising BF systems" is M12

2.5 Site-specific literature list

2.5.1 Publications (journals, conferences….)

Lorenzen, G., Sprenger, C., Taute, T., Pekdeger, A., Mittal, A., Massmann, G., (2010) Assessment of the potential for bank filtration in a water-stressed mega city (Delhi, India) Environmental Earth Sciences, Volume 61, Number 7H, 1419-1434, DOI: 10.1007/s12665-010-0458-x

Pekdeger, Lorenzen, Sprenger (2008) Preliminary report on data of all inorganic substances and physicochemical parameters listed in the Indian and German Drinking Water Standards from surface water and groundwater at the 3 (+1) field sites. TECHNEAU Integrated Project, European Commission, deliverable D5.2.1; available: http://www.techneau.org/index.php?id=120

Silva, S.R, Kendall, C., Wilkison, D.H., Ziegler, A.C, Chang, C.C.Y., Avanzino R.J. (2000) A new method for collection of nitrate from fresh water and the analysis of nitrogen and oxygen isotope ratios, Journal of Hydrology 228, 22–36

3 Haridwar RBF site

3.1 Synthetic site description

Haridwar is one of the most important Hindu pilgrimage sites in the world. In this context, on a single auspicious day, as many as 10 million pilgrims are estimated to bathe in the Ganga River and Upper Ganga Canal (Figure 10), which serve as a source of the bank filtrate abstracted by the 22 RBF wells (Figure 11). During such religious gatherings, not only does the water supply of Haridwar have to effectively meet extreme surges in demand, but it also has to cater to the constant demand of the permanent population of > 225,000 persons (Census of India, 2011). This, and the demographic fact that by 2011 the permanent urban population of Haridwar had increased by around 63 % since 2001 (Census of India, 2011), are important considerations for the management of the Haridwar's water supply.

Figure 10 Haridwar town, UGC (foreground) and Ganga River (background).

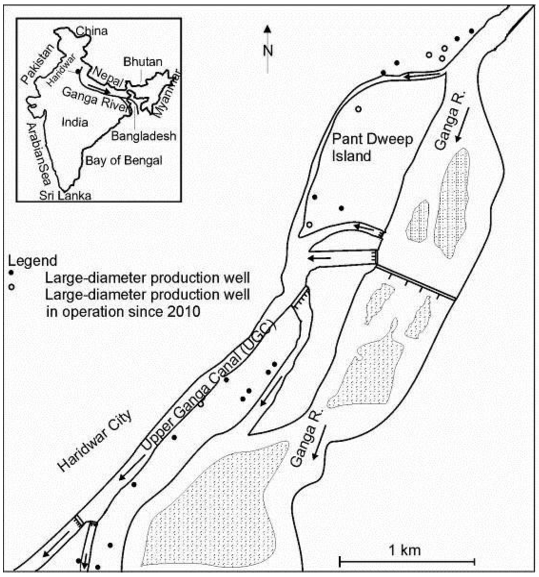

Figure 11 RBF wells in Haridwar.

Haridwar is the administrative headquarters of the Haridwar district (2360 km^2). The district experiences a moderate sub-tropical to humid climate, with the main seasons being summer, monsoon and winter. The average annual rainfall in Haridwar district is 1174 mm (recorded at the weather station in Roorkee, 30 km SW of Haridwar), out of which 84 % is received during monsoon and 16 % occurs during non-monsoon (CGWB, 2009). The CGWB (2009) states the presence of a multi-layered aquifer system occurring under unconfined, semi-confined and confined conditions, separated by thick clay layers. It also states that the groundwater chemical parameters are well within permissible limits and suitable for drinking (IS 10500, 1991) and irrigation purposes. Studies regarding the efficiency and sustainability of RBF commenced on Pant Dweep Island (Figure 11) in 2005 (Dash et al., 2010; Sandhu et al., 2010, 2011). These studies report the unconfined aquifer on Pant Dweep to comprise fluvial deposits to a depth of 20 m below ground and sediments ranging from fine sand and silt to medium sand and gravel. The deposit is overlain by Holocene river boulders. The aquifer can be described as a single-layer system which is in direct hydraulic contact with the river and the canals surrounding Pant Dweep. These studies report that bank filtrate abstracted from a production well on Pant Dweep Island, when compared with Ganga River water, showed significant removal of total coliforms, E. Coli, turbidity and organics for travel time of 77–126 days. The abstracted water from all the RBF wells in Haridwar only requires disinfection by chlorination, and provides safe drinking water even when facing high variations in water demand (such as during the Kumbh and Ardh Kumbh Melas) and during monsoons (Sandhu et al., 2011).

However, following one of the severest monsoons in North India and as reported by the Central Water Commission of India, the Ganga River rose to an unprecedented level of 296 m above sea level on 19 September 2010, inundating the ground surface around the nearby wells. The water in the wells became turbid and for over 48 hours, the wells were operated continuously and all the abstracted water was discharged back into the river until the turbidity disappeared. It is believed that the sharp increase in turbidity was the result of the floodwater percolating down the well shaft. In WP5, site data from Haridwar will be used to develop a conceptual model as a base for formulating suggestions for monitoring and operation during floods.

Drinking water production by riverbank filtration: The permanent population of the entire urban agglomeration of Haridwar that includes the outgrowths (suburban areas) was 310,582 persons according to the 2011 census, out of which 225,235 persons permanently reside in the main or core city area (Census of India, 2011). The bank filtrate abstracted from 22 large-diameter (10 m) caisson wells is supplied solely within the limits of the main city (Figure 11). Being one of the most important Hindu pilgrimage sites in the world, Haridwar has a “floating” population of around 200,000 persons who reside temporarily within the main city in religious retreat locations (“Ashrams”) and hotels, and an additional 400,000 – 500,000 persons (mainly pilgrims) visit the main city every day (Uttarakhand Jal Sansthan, 2012). Accordingly, the production from the 22 RBF wells accounts for nearly 50 % (> 43,000 m^3/day) of the total drinking water demand of the entire population within the main city. Groundwater abstraction through vertical production wells ("tube" wells) covers the remainder of the drinking water demand in the main city.

3.2 Previous projects

Project acronym/name: Indo-German Riverbank Filtration Network (RBFN)

Duration: from 01.09.2008 to 31.12.2010

Framework: German Federal Ministry of Education and Research (BMBF) funding, within its programme "India and Germany – Strategic Partners for Innovation".

Coordination/partnership: HTWD (coordinator). Partners: UJS, water company Stadtwerke Düsseldorf AG, IITR and Cooperation Centre for Riverbank Filtration (CCRBF)

What was done: As a component of the RBFN project, a groundwater flow model using PMWIN was constructed for Pant Dweep Island (Figure 11) to obtain an improved understanding of the groundwater flow pattern and to determine the travel-time and flow-path of bank filtrate on Pant Dweep (Sandhu et al., 2010). The model was calibrated for steady-state conditions. Transient simulations were conducted for a one year period covering the main seasons of monsoon, post-monsoon (winter) and pre-monsoon (summer) to understand the travel-time and flow-path of bank filtrate under changing surface water flow conditions over the one year period around Pant Dweep (changes in water levels). Due to the extremely sparse data-set, a validation of the simulated groundwater heads was not possible.

3.3 Existing models

See above (section 3.2)

3.4 Models to be developed

3.4.1 Objectives of Saph Pani modelling work

The main aims of modelling the RBF sites in Haridwar are to:

- Obtain an understanding of the existing groundwater and bank filtrate flow patterns and travel-times for the area to the north and south of Pant Dweep island where 18 RBF wells are located in Haridwar
- Optimise operating conditions, taking into account the specific hydroclimatic conditions (monsoon-induced floods)
- Develop a decision support system for optimum design and operation of BF schemes in India under varying hydrological, geological and hydrochemical conditions, design criteria for optimum pathogen and pesticide removal

3.4.2 Target groups, potential endusers of SAPH PANI models

It is expected that the models will continue to be used by the researchers (who developed them) after completion of the project to develop guidelines for general scenarios. It is not expected that the water companies themselves will use the model.

3.4.3 Model type

Time scale, steady-state or transient state: both

Spatial scale: local (approximately 6 km^2)

1D-3D: 3D finite difference

Flow and transport: mainly flow-model for Haridwar and Srinagar

(Geo)chemical model, reactive flow: no

Other relevant points: The reason why the new RBF site in Srinagar has additionally been chosen is mainly because Haridwar has extremely regulated surface flow-conditions (as a result of numerous flow control mechanisms on the Ganga river and UGC) that are atypical for Indian conditions. On the other hand, Srinagar represents a more natural condition that will enable the simulation of receding water-line of the river during non-monsoon seasons and dynamic flow during the monsoon.

3.4.4 Modeling tools to be used

Tools for data management: MS-Excel and ArcGIS

Tools for modelling: PMWin, Visual Modflow

Only existing tools will be used, no development of model software is planned within the project?

3.4.5 Modeling tasks and responsible partners

HTWD: Co-modelling (with NIH) of Haridwar, testing the use of the isotope Rn-222

NIH: Modelling of Haridwar RBF site and isotope measurements

UJS: Assistance in data collection

NIH, HTWD & UJS: Baseline geological, hydrogeological and hydrological data collection

NIH & HTWD: Geochemical investigations, hydrogeological investigations (pumping tests, tracer tests). Residence time structure and the river-groundwater interactions in the groundwater bodies will be investigated through geochemical (SF6, CFCs – in cooperation with BRGM if BRGM can conduct the analyses) and isotopic tracers (δ18O, δ2H) in order to calibrate the groundwater models. Pumping tests, surface and groundwater level measurements will be conducted by UJS at the RBF site in Haridwar.

3.5 Conceptual Model of the study site

The RBF wells in Haridwar (Figure 11) have some significant features, which suggest the need for a comprehensive analysis of the flow fields of the 22 wells together. These features are e.g. the 22 large diameter (10 m) RBF caisson wells with depths ranging from 6 to 10 m spaced closely in series in an island type area having hydraulically connected boundaries at both sides at different distances. Furthermore, as the wells are spaced closely, there is every possibility that the flow field of one well is influenced by another wells flow field. The wells with river boundaries at both sides will have different flow patterns than the wells drawing water from a one-sided river boundary. It is, therefore, pertinent to consider the simulation of 22 RBF wells together under a comprehensive common computational framework. A 3-dimensional finite difference scheme using the Visual MODFLOW coupled with MT3D (ver. 1.5) software is thus conceptualized for modelling of aquifer responses due to pumping of RBF wells for variable hydrologic and hydraulic conditions including modelling of contaminants' transport.

3.6 Status of numerical modelling at M12

3.6.1 Geometry and geo-hydraulic characteristics

The spatial extent of the model area is 5000 m in x-direction and 6000 m in y-direction. Vertically the study area is divided into three layers. The thickness and a first definition of their geo-hydraulic characteristics are shown in Table 1. Figure 12 shows the prepared vertical distribution of the model area visualized in Modflow.

Table 1 Characteristics of the modelled layers for RBF-Site Haridwar

Layer	depth [m bGL]	hydraulic conductivity [m s^{-1}] (Sandhu et al. 2010)
1	6 - 12	Kx=Ky= 3.7E-04 Kz=2.6E-05
2	12 - 35	Kx=Ky= 3.7E-04 Kz=2.6E-05
3	35 - 45	Kx=Ky= 2.7E-04 Kz=2.6E-05

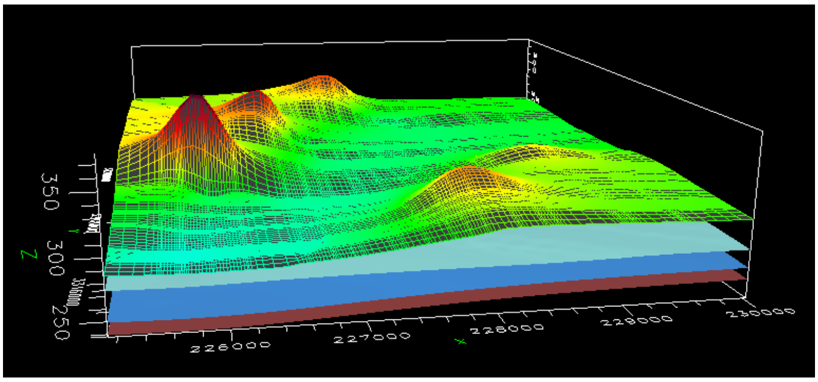

Figure 12 Vertical distribution of the modelled RBF-Site Haridwar

As elucidated in Dash et al. (2010), the aquifer is in direct hydraulic contact with the Upper Ganga Canal, the New Supply Channel and the Ganga River. Therefore the surface water bodies are defined as a river-boundary condition. Riverbed elevations and widths are estimated by detailed cross-section data and the hydraulic riverbed characteristics are defined after Sandhu et al. (2010). The mountains in the western part and the cells next to the river in the eastern part of the model area are assigned as inactive cells (green areas in Figure 13). Initial heads for the northern and southern model-boundary are derived by interpolating the surface and corrected groundwater level measurements for particular days. The horizontal cell-size of the rectangular model grid is between 12.5 and 100 m (Figure 13b).

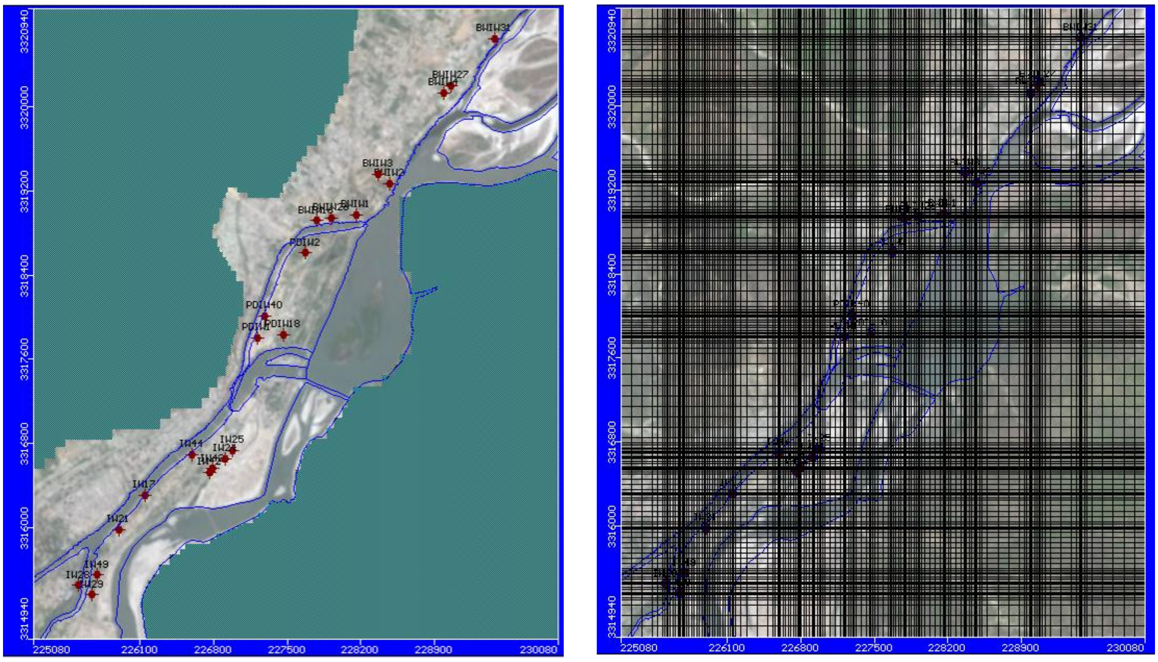

Figure 13 (a) Conceptualized model domain area of the 22 RBF wells in Haridwar. (b) Discretized model domain

3.6.2 Flow modelling

The model input data pertaining to (i) initial domain conditions, (ii) aquifer parameters, (iii) pumping rates, (iv) river stages & geometry and (v) recharge are being prepared in accordance with the computational framework. Further, boundary conditions, pumping rates, river stages, and other stresses are time variant variables; therefore, a transient-state model is conceptualized. For calibration of the model parameters, a steady-state condition is conceived. Thus, a huge task involving collection and preparation of input data is required.

3.6.3 Progress

Construction of model framework for flow modelling has been completed. A Digital Elevation Map (DEM) of the modelling area has been prepared. A first definition of the hydraulic characteristics of every model layer has been done. Each cell (active and inactive) is classified. First model-run and calibration is under progress. Data collection works are progressing simultaneously. Referring to the meteorological data (rainfall, wind speed, minimum and maximum temperature, relative humidity from 2004-2008 and requested data for 2012) stresses like evapotranspiration and recharge will be calculated referring to already researched literature.

As baseline data for the flow modelling, borehole data for 3 locations, river cross-sections, hydraulic conductivity of the riverbed of the Ganga River, topographic data (ASTER DATA) had been collected. River stages and discharges data is being collected. Ground verification of distances of wells from the river and canal bank as well as pumping tests are also under progress.

As a routine task, periodic water sampling from 22 RBF wells, from river at four locations, from groundwater at 24 locations, and measurement of groundwater levels are carried out. River and groundwater samples are also collected for isotopic analysis. Up to now from 27th July, 3 times sampling and 7 times water levels measurements on different dates have been carried out. Water samples are analyzed in the Water Quality Laboratory of NIH to determine 21 water quality constituents, namely; Temperature, pH, EC, TDS, Hardness, Turbidity, Alkalinity, Chloride, SO_4^{2-}, NO_3^-, Na^{2+}, K^+ , Ca^{2+}, Mg^{2+}, Fe^+, Mn^+, HCO_3^-, Total Coliform, Fecal Coliform, BOD and COD. Water samples are also analyzed to determine the isotopic character of water in the Nuclear Hydrology Lab. of NIH.

3.7 Site-specific literature list

3.7.1 Publications (journals, conferences….)

CGWB (2009) Groundwater Brochure of Haridwar District, Uttarakhand. Government of India, Ministry of Water Resources, Central Ground Water Board (CGWB), Uttarakhand Region, Dehradun.

Census of India (2001) 2001 Census Results. Census of India, Office of the Registrar General, New Delhi.

Census of India (2011) 2011 Census Results. Census of India, Office of the Registrar General, New Delhi.

Dash RR, Bhanu Prakash EVP, Kumar P, Mehrotra I, Sandhu C and Grischek T (2010). River bank filtration in Haridwar, India: removal of turbidity, organics and bacteria. Hydrogeology Journal, 18(4), 973-983.

IS 10500 (1991) Indian standard (IS) specifications for drinking water. Bureau of Indian Standards, New Delhi, India.

Sandhu C, Schoenheinz D and Grischek T (2010) The impact of regulated river-flow on the travel-time and flow-path of bank filtrate in Haridwar, India. In: Zuber A., Kania J., Kmiecik E. (Eds.) Extended Abstracts, 38. IAH Congress, 12.-17.09.2010, Krakow, 2299-2305.

Sandhu C, Grischek T, Kumar P and Ray C (2011). Potential for riverbank filtration in India. Clean Technologies and Environmental Policy. 13(2), 295-316.

3.7.2 Other accessible data

All publications under Section D “Literature list” are publicly accessible

Healy RW and Cook PG (2002): Using groundwater levels to estimate recharge. Hydrogeology Journal. DOI 10.1007/s10040-001-0178-0.

Kumar CP (no date): Groundwater Assessment Methodology. National Institute of Hydrology, Uttarakhand India.

Sachse R (2005): Drinking Water Abstraction by River Bank Filtration (RBF). Report of Investigantion in Haridwar, India. University of Applied Sciences Dresden.

4 Srinagar RBF site

4.1 Synthetic site description

The town of Srinagar is located on the road to the important Hindu shrine of Badrinath in the Himalayas. The combined drinking water production for Srinagar and the town of Pauri (the water for which is abstracted and treated in Srinagar before being pumped 29 km to Pauri at an altitude of around 1660 m above MSL) in 2010 was around 3,750 m^3/day in contrast to a total demand of approximately 4,880 m^3/day (Kimothi et al. 2012). Currently around 80 – 82 % of the total raw water for the drinking water supply of Srinagar and Pauri is abstracted upstream of the town directly from the Alaknanda River. The abstracted surface water is passed through rapid sand filters and chlorinated before being supplied to the distribution network. However, similar to Haridwar, in the severe Monsoon of 2010 the surface water supply had to be discontinued due to excessive turbidity. Additionally the completion of a tunnel to divert a major portion of the flow for a river-run hydropower generation plant, the river will have a severely reduced flow along a 4 km stretch rendering current surface water abstraction system inoperable. Preliminary investigations show promising conditions for RBF in Srinagar (Figure 14; Sandhu et al. 2011). Although the flow of the Alaknanda River is sufficient throughout the year, over the period from the peak-monsoon (August–October) flows to the post-monsoon (January–February) flows the waterline can recede by as much as 190 m from the southern bank of river, especially in the area of the production well at Silk Farm. This would significantly influence the travel-time of bankfiltrate and result in changing redox conditions. On the other hand, extreme events like the monsoon of 2010 and 2011 resulted in the water-line of the river reaching within a few metres of the wells. Additionally, in land-side groundwater, high nitrate concentration was found, assumed to come from urban pollution with sewage.

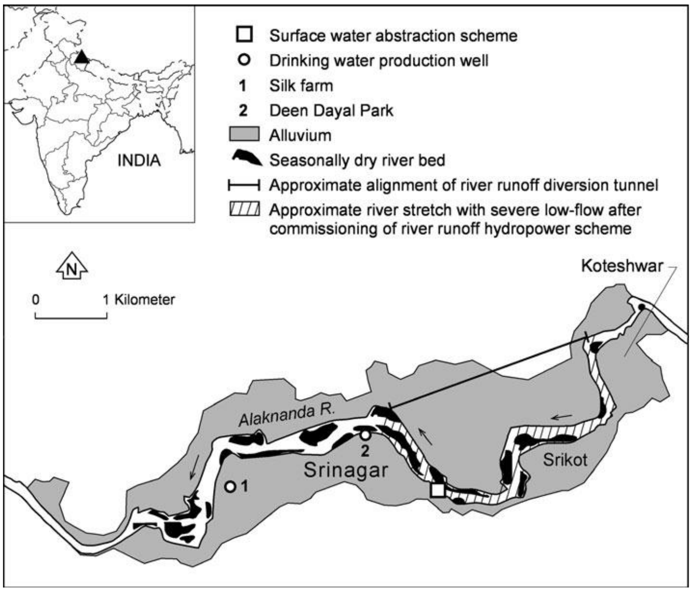

Figure 14 Srinagar, with the location of the new RBF site (1) (from Sandhu et al. 2011).

In May 2010, one production and one monitoring well (PW-DST & MW1) were constructed in the south-west part of the town (Figure 15) as part of a separate project (Kimothi et al. 2011). The wells were drilled up to a depth of 20 m BGL and at a distance of 170 m from the flood-protected riverbank. The interpretation of the borehole material showed that the aquifer comprises medium to coarse sand. Interpretation of pumping test data from PW-DST showed the hydraulic conductivity to be in the range of 7.7×10^{-5} – 4.0×10^{-3} m/s. The PW-DST currently operates for 20 – 22 hours/day with a production of 852 – 937 m^3/day. After abstraction and on-site disinfection by chlorination, the water is pumped into a storage reservoir and then supplied into the distribution network by gravity. The production from the PW-DST accounts for 18 – 22 % of the combined drinking water production of Srinagar and Pauri (Kimothi et al. 2012).

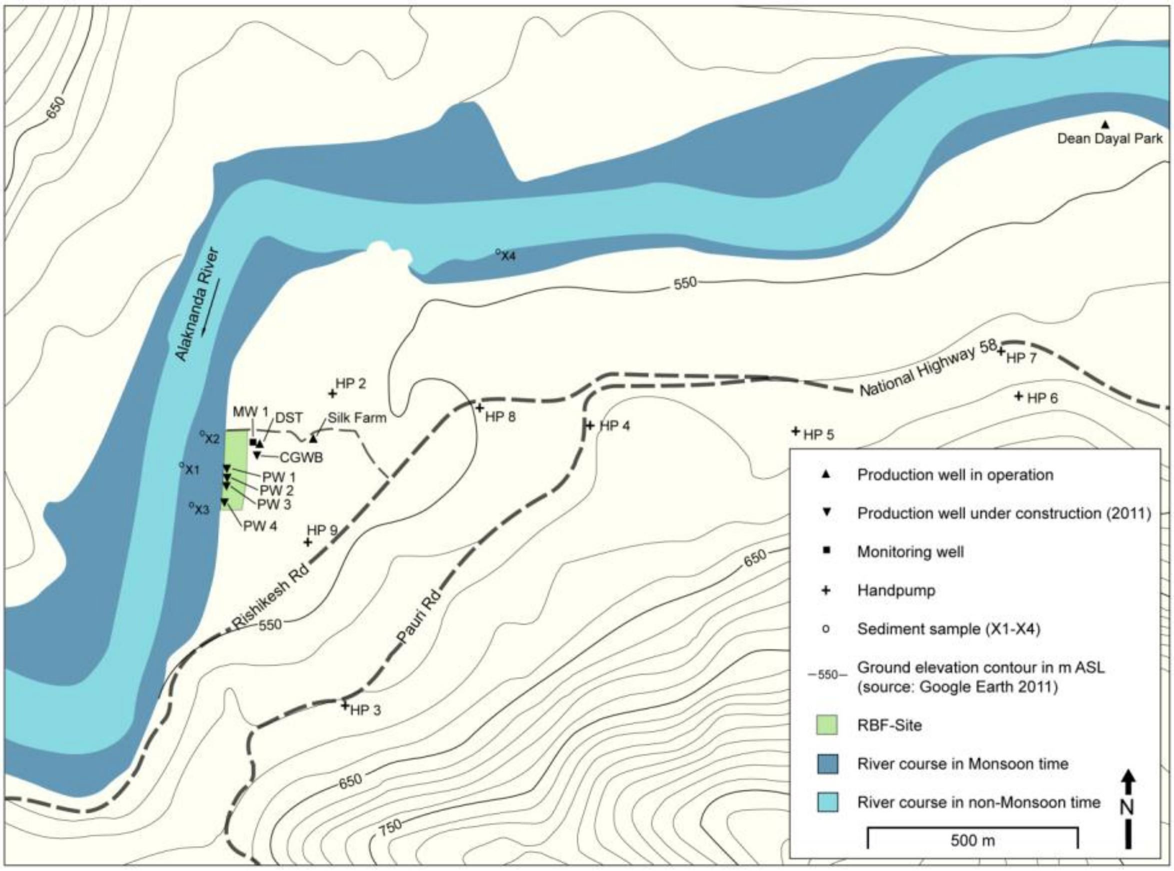

Figure 15 RBF well field in Srinagar under development since May 2010

In the period July – September 2011, four additional boreholes were drilled and casings, filter sections and filter gravel were installed in Srinagar in the area in between the wells drilled in 2010 and the river (Figure 15 and Figure 16, PW-DST & PW1…PW5). The PW-DST installed in 2010 revealed suitable hydrogeological conditions for RBF, although high nitrate concentrations (> 50 mg/L) in the abstracted water were observed after pumping commenced in 2010 with the abstraction of predominantly ambient groundwater. As potential exists in Srinagar to construct additional RBF wells near to the existing PW (2010), such a system of a battery of wells along the river will not only cater to future increases in demand, but will also increase the proportion of bank filtrate abstracted by the wells. An increased proportion of bank filtrate in the abstracted raw water is particularly useful in case of undesired high concentrations of nitrate in land-side groundwater. High nitrate concentrations in groundwater is a common occurrence in areas where agricultural activities lead to widespread fertiliser application or wastewater from leaky urban drains and sewers comes in contact with groundwater. Consequently, mixing of bank filtrate with ambient groundwater would lower the concentration in the water pumped by the well.

Figure 16 Four additional boreholes for production wells were drilled in July - September 2011 (Photo: F. Musche & E. Ballmann, HTWD, 2011)

Within the framework of the Saph Pani project, a monitoring well (MW4) was constructed in May 2012 by the project partners Akshay Jaldhara and Uttarakhand Jal Sansthan in between PW4 and the river (Figure 17). MW4 is 15.1 m deep and is situated at a distance of 4 m from the flood-protected river bank and 0.75 m from PW4. The close proximity to the high-flow mark of the river is intentional in order to investigate the removal efficiency of pathogens during monsoons and floods. The determination of the removal efficiency of pathogens, by comparing the total and fecal coliform counts of the abstracted water from PW4 and the Alaknanda, commenced in end September 2012.


a


b

Figure 17 (a) Monitoring well MW4 (left) constructed in Srinagar in between PW4 and the Alaknanda (Photo: K. Heinze, HTWD, May2012) (b) Pumping test and sampling being conducted on MW4 & PW4 (Photo: V.D.A. Nguyen, HTWD, September 2012)

4.2 Previous / Parallel project(s)

Project acronym/name: Development of Riverbank Filtration in Hill Regions for Sustainable Solution for Quality and Quantity Problems of Drinking Water in Uttarakhand

Duration: from 2010 – 2013

Framework: "Water Technology Initiative" of the Department of Science and Technology, Government of India (DST-WTI).

Coordination/partnership: Uttarakhand State Council for Science and Technology (UCOST). Partners: UJS and Cooperation Centre for Riverbank Filtration (CCRBF)comprising HTWD, IITR and water company Stadtwerke Düsseldorf AG

What was done: One production well (PW) and one monitoring well (MW) have been constructed at RBF sites in each of the four towns of Srinagar, Karnaprayag, Agastmuni and Satpuli. The PW in Srinagar and Satpuli are already abstracting water regularly and are connected to the drinking water supply network of these towns. As such, the development of RBF in hill-regions has commenced. Consequently the formulation of concepts for the quick selection of RBF sites is in progress.

Website or information on the web: no

4.3 Existing models

No previous modelling work was done for Srinagar.

4.4 Models to be developed

4.4.1 Objectives of Saph Pani modelling work

The main aims of modelling the RBF site in Srinagar are to:

- Obtain an understanding of the existing groundwater and bank filtrate flow patterns and travel-times for the RBF site in Srinagar
- Optimise operating conditions such that the proportion of bank filtrate is maximised in order to lower the concentration of nitrate abstracted by the well, taking into account the specific hydroclimatic conditions (monsoon-induced floods) resulting in a change of river channel due to dynamic flow conditions.

4.4.2 Target groups, potential endusers of SAPH PANI models

It is expected that the results of the model will directly help UJS as a decision support tool.

4.4.3 Model type

Time scale, steady-state or transient state: both

Spatial scale: local (approximately 2.4 km^2)

1D-3D: 3D finite difference

Flow and transport: mainly flow-model for Haridwar and Srinagar

(Geo)chemical model, reactive flow: no

Other relevant points: The reason why the new RBF site in Srinagar has additionally been chosen is mainly because Haridwar has extremely regulated surface flow-conditions (as a result of numerous flow control mechanisms on the Ganga river and UGC) that are atypical for Indian conditions. On the other hand, Srinagar represents a more natural condition that will enable the simulation of receding water-line of the river during non-monsoon seasons and dynamic flow during the monsoon.

4.4.4 Modeling tools to be used

Tools for data management: MS-Excel

Tools for modelling: PMWin, only existing tools will be used, no development is planned within the project

4.4.5 Modeling tasks and responsible partners

HTWD: Modelling of Srinagar RBF site and testing the use of the isotope Rn-222 and / or a fluorescent tracer

UJS, HTWD & IITR: Baseline geological, hydrogeological and hydrological data collection, geochemical investigations, hydrogeological investigations (pumping tests, tracer tests). Residence time structure and the river-groundwater interactions in the groundwater bodies will be investigated in order to calibrate the groundwater models. Pumping tests, surface and groundwater level measurements will be conducted by HTWD, UJS and ITR at the RBF site in Srinagar.

4.5 Groundwater flow model

4.5.1 Model set-up

A groundwater flow model was constructed using PMWIN (version 8.03) for the area covering around 2.4 km^2 shown in Figure 15. Based on a reference day measurement of the ground and surface water levels on 10.12.2011, a groundwater contour map was prepared using the triangulation method. This map was then used as a base map in the model whose domain was divided initially into 16 rows and 15 columns with a starting cell size of 100 × 100 m. The model-grid around the production wells was refined to 0.34 × 0.34 m, and to 20 × 20 m to 50 × 50 m and thereby finally resulting in a model domain of 37 rows and 35 columns. The ground surface elevation in the model was prepared by interpolating the actual levels determined from the survey of the site. The thickness of the aquifer was determined to be 21 m as interpreted from borehole logs of the production wells PW-DST, silk farm and PW1 to PW4. Accordingly a subsurface cross-section was constructed for the RBF site (Figure 18).

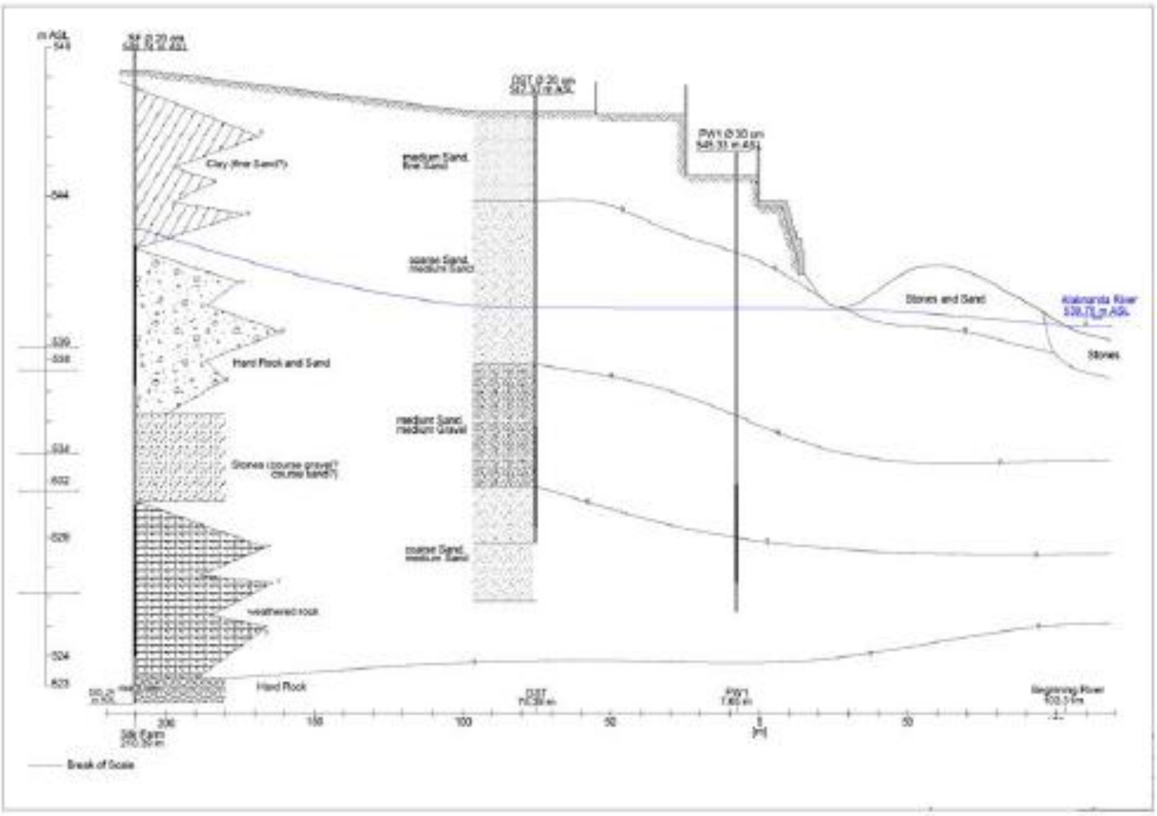

Figure 18 Subsurface cross section of RBF site in Srinagar

The input parameters of the model are summarised in Table 2. The river in the model was assigned as constant head cells. The horizontal hydraulic conductivity of the riverbed was assigned to the model as a mean value of 4.5×10^{-2} m/s obtained after Beyer from sieve analyses of sediment taken from four different locations along the river, with a vertical hydraulic conductivity of 4.5 × 10^{-3} m/s. A horizontal hydraulic conductivity of 1.3 × 10^{-3} m/s obtained from pumping tests was assigned for the aquifer in the near-bank area along the entire river, with a vertical hydraulic conductivity estimated at 1.3 × 10^{-4} m/s. The effective porosity was set at 0.3. A recharge value of 3.96 × 10^{-8} m/s was assigned to the model based on a mean precipitation for the period 1965 – 1986 for the region of Srinagar. Due to the absence of site specific borehole data, the hill slope in the model above the relatively level RBF site was assigned a lower hydraulic conductivity of 6 × 10^{-6} m/s. Information obtained from a report of the construction of a dam a short distance upstream of Srinagar, indicates that a thin layer of topsoil covers a predominantly hard rock layer mostly in areas with a steep topography.

Table 2 Summary of groundwater flow model parameters for Srinagar RBF site

Model parameter	Assigned value
Geometry	Area: 1600 × 1500 m; 37 rows, 35 columns; cell size: 0.3 × 0.3 m to 100 × 100 m
Boundary conditions	River: assigned as constant head cells along western and northern boundary, interpolation of water levels measured on 10.12.2011
	Wells: total discharge of 0.06 m^3/s (5184 m^3/day) at 0.01 m^3/s per well for six production wells (PW-DST, PW-CGWB and PW1 to PW4)
	Recharge: 3.96 × 10^{-8} m/s assigned to uppermost active cells
Hydraulic conductivity	River cells: $K_x = K_y = 1 \times 10^{-3}$ m/s; $K_z = 1 \times 10^{-4}$ m/s
	Aquifer in flood plain area: $K_x = K_y = 3 \times 10^{-3}$ m/s; $K_z = 3 \times 10^{-4}$ m/s
	Hill-side slope: $K_x = K_y = 6 \times 10^{-6}$ m/s; $K_z = 6 \times 10^{-7}$ m/s
Effective porosity	0.3
Simulation	Steady state , unconfined conditions

4.5.2 Calibration

The flow model was calibrated for a steady state to the reference day measurements of 10.12.2011 (Table 3). For the observation points (including the production well) DST, PW1, CGWB and HP 8, a relatively good calibration is achieved. However a significant variation occurs for the points HP 3 and 4. This is likely to be a consequence of the local geology and groundwater flow conditions in the vicinity of these points, for which more detailed information is unavailable.

Table 3 Observed and calculated heads for the calibrated flow model for Srinagar

OBSNAM	Calculated Value [m ASL]	Observed Value [m ASL]
DST	539.79	539.08
PW 1	539.63	540.30
CGWB	539.79	540.37
HP 3	588.92	592.11
HP 4	542.18	558.70
HP 8	541.80	540.30

4.5.3 Initial results

Backward particle tracking was conducted using PMPATH (V. 6.5.0) to determine the flow path and travel time of the bank filtrate to the wells (Figure 19). It is observed that for a total production of 5184 m^3/day, that would eventually be attainable when all six wells (PW-DST, PW-CGWB, PW1, PW2, PW3 and PW4) start operation in the well field, and for a low flow condition in the Alaknanda River (that dominates for 8-9 months a year) the wells would abstract relatively old bank filtrate (650 days). The bank filtrate would mainly originate from the river to the north-east of the RBF wells and travel across the meander. This will also result in a greater risk of the bank filtrate being affected by anthropogenic factors such as domestic sewage and wastewater. Thus this also supports the explanation for the high nitrate in the abstracted water.

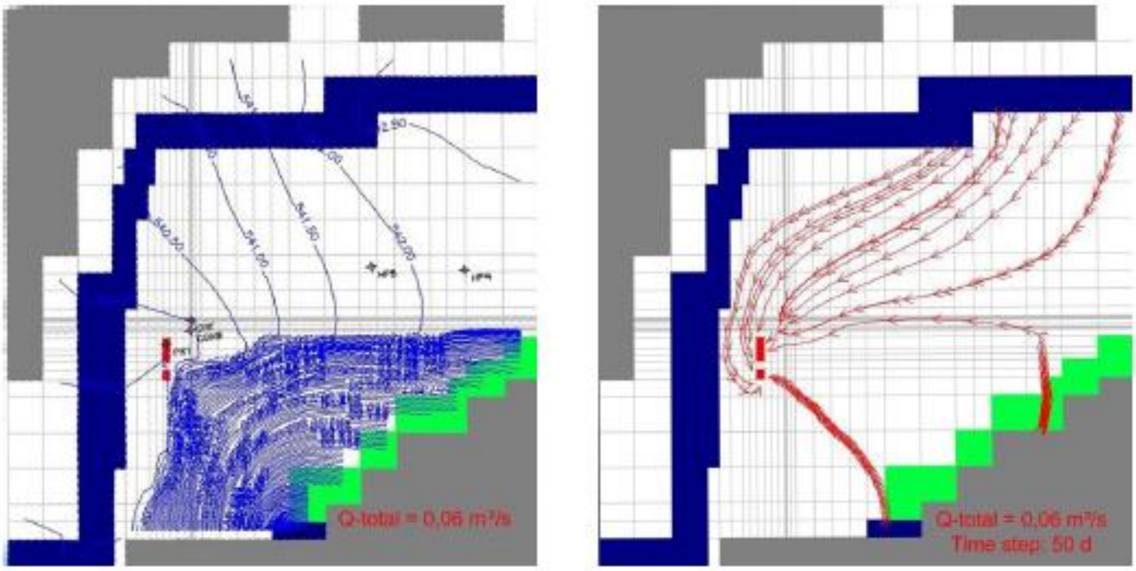

Figure 19 Simulated groundwater contours, travel time and flow path for the current scenario wherein the total abstraction from the RBF well field is 0.06 m^3/s

However in order to achieve a higher proportion of bank filtrate in the abstracted water, the total abstraction from the well field would have to be significantly increased to at least 0.3 m^3/s. This will result in a bank filtrate originating from directly along the river adjacent to the well field (Figure 20).

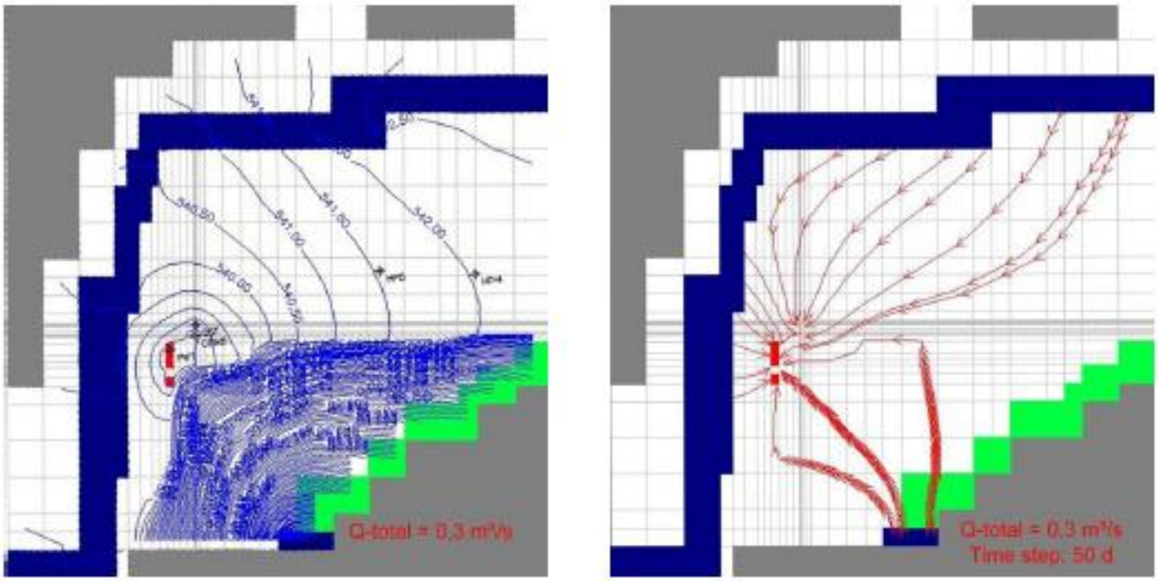

Figure 20 Simulated groundwater contours, travel time and flow path for a fictive scenario wherein the total abstraction from the RBF well field is 0.3 m^3/s

4.6 Further work

The initial results obtained from the steady state flow model described in the previous section provide a prognosis of the flow path and travel time of the bank filtrate for existing operating conditions as of September 2012. Considering the fact that the radius of influence of the production wells with existing abstraction rates does not reach the river on the western boundary of the well field during non-monsoon months (October – June), an abstraction of bank filtrate over the optimal direct and shortest flow path of up to 170 m will not occur except during the monsoon.

In order to optimise the proportion of bank filtrate abstracted directly from the river from the west (and not from the north east side), a continuous operation of all six production wells is necessary.

Currently, frequent water level measurements are being conducted in the field. The aim is to use these measurements to conduct a transient simulation. The transient simulation will enable a prognosis of the effect of the monsoon on the proportion and travel time of the bank filtrate. It is expected that the monsoon will have a positive effect by increasing the proportion of bank filtrate abstracted directly from the river during the monsoon because the river channel is completely inundated and the water line of the river reaches the bank. On the other hand, coupled with the water quality measurements on pathogen removal, the transient model will also provide a prognosis of the risk (based on travel-time and field measurements of coliforms) of the monsoon towards pathogen removal at this RBF site.

Furthermore, the geometry of the initial steady state model needs to be optimised. Due to the scarce information on the subsurface lithology, the location and type of boundaries need to be reviewed.

4.7 Site-specific literature list

Kaur R, Kendall T (2008) Myth of power. Down To Earth, 17(8), 28–32.

Kimothi PC, Adlakha LK, Dobhal R, Ronghang M, Sandhu C, Grischek T, Kumar P, Mehrotra I, Voltz TJ, Rawat OP, Patwal PS (2011) Development of Riverbank Filtration in Hill Regions for Sustainable Solution for Quality and Quantity Problems of Drinking Water in Uttarakhand. Intermediate Project Report: March 2010 – December 2011, funded by "Water Technology Initiative" of the Department of Science and Technology, Government of India (DST-WTI).

Kimothi PC, Dimri DD, Adlakha LK, Kumar S, Rawat OP, Patwal PS, Grischek T, Sandhu C, Ebermann J, Ruppert M, Dobhal R, Ronghang M, Kumar P, Mehrotra I, Uniyal HP (2012) Development of Riverbank Filtration in Uttarakhand. *J. Indian Water Works Association*, July–September issue (*in press*).

Sandhu C, Grischek T, Kumar P and Ray C (2011). Potential for riverbank filtration in India. Clean Technologies and Environmental Policy. 13(2), 295-316.

5 Musi River site

5.1 Site specific background knowledge

5.1.1 Synthetic site description

The Musi River (Figure 21) which flows through the city of Hyderabad is associated with an ancient irrigation system comprising a series of (natural/engineered) wetlands. The river receives over a 1.2 million m^3 /day of wastewater (both domestic and industrial) from the city which is only partially treated and used for irrigation, either directly via a system of irrigation canals or after storage in sedimentation tanks. The wastewater is a significant resource in this semi-arid periurban environment where the cultivation of fodder grass, paddy and vegetables has provided economic benefits to many inhabitants of the area. Year round cultivation, which generates large return flows from irrigated fields, contributes to a large share of the aquifer recharge. Shallow groundwater is also pumped locally for irrigation on terrains where canal water is not accessible, or where it is too polluted for certain crops, especially paddy rice (Amerasinghe et al., 2008). The Musi river flow is broken by a series of weirs, creating small small reservoirs, from where water is diverted into irrigation canals and village tanks to be used by farmers for crop production (Ensink et al. 2009).

Saph Pani studies will be carried out in the “Kachwani Singaram” catchement (wetland), which is situated in the left bank of the Musi River, and is around 10 km away from the city of Hyderabad (Schmitt, 2010, Perrin et. al, 2011). It is one of the rice growing regions close to the city and constitues around 2.74 km^2, dominated by wastewater irrigation. Other crops are paragrass and vegetables.

Hydrogeologcial conditions: composed of orthogneissic granite as basement with granite, quartz and dolerite intrusions. For details see reports of Schmitt (2010), Perrin et al. (2011) and Aellen, (2011).

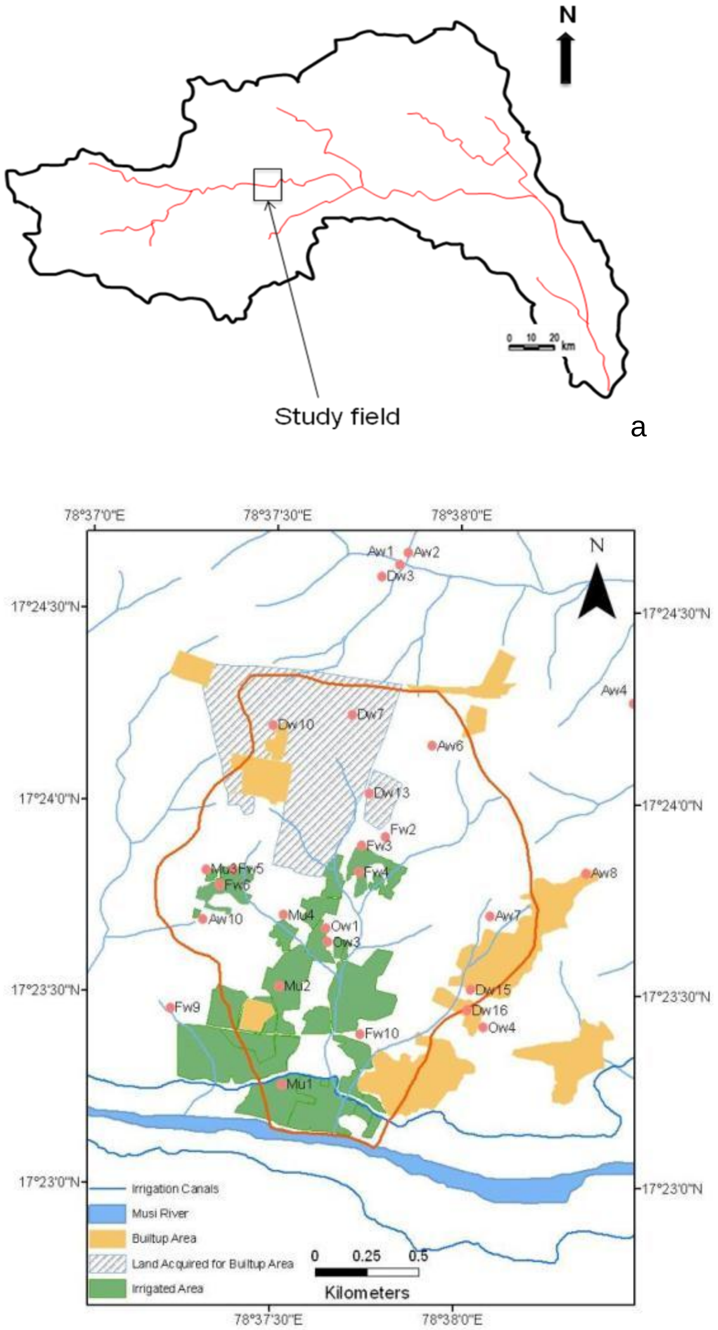

Figure 21 (a) Situation of the Kachwani Singaram Micro-Watershed in the Musi River basin, (b) Spatial Distribution and Land use map

5.1.2 Previous projects

Project acronym/name: **Assessing groundwater processes in a periurban micro-watershed in Hyderabad.**

Duration: 2009/2010

Framework: IWMI funding

Coordination/partnership : IWMI, BRGM, NGRI (IFCGR)

What was done: An area (280 ha) comprising wastewater- and groundwater-irrigated agriculture was selected for detailed study based on land-use maps and observations. The watershed was delineated using DEM and GIS data. A crop model (BUDGET; Raes, 2005) was combined with field measurements, baseline data on irrigation practices, and land use patterns, to assess the overall water balance. The suitability of the method was validated with questionnaire survey results and available secondary data. Four piezometers were installed to assess and monitor groundwater levels and quality. Base-line data for 23 distinct fields were collected.

Master Thesis: Schmitt, 2010 "Wastewater reuse in Indian peri-urban agriculture Assessment of irrigation practices in a small, peri-urban catchment in Hyderabad, Andhra Pradesh, India"

Website or information on the web: none

Project acronym/name: **Assessing groundwater processes in a periurban micro-watershed in Hyderabad.**

Duration: 2009/2010

Framework: IWMI funding

Coordination/partnership: IWMI, BRGM, NGRI (IFCGR)

What was done: This study defined the impact of different types of irrigation water (surface water, mix water between canal water and groundwater, and groundwater) on groundwater quality, determine the interaction between Musi river and groundwater, characterized the aquifer properties (piezometric map, transmissivity, conductivity, groundwater budgeting) in the representative hydrogeological unit of Kachwani Singaram and evaluated the impact of scenarios of future water uses on the groundwater system.

Project Report: Perrin et al. 2011 "Groundwater processes in a micro-watershed influenced by wastewater irrigation, peri-urban Hyderabad."

Website or information on the web : none

Project acronym/name: **Assessing groundwater processes in a periurban micro-watershed in Hyderabad.**

Duration: 2009/2010

Framework: IWMI funding

Coordination/partnership: BRGM, NGRI (IFCGR), IWMI

Master Thesis: Aellen, 2011.

What was done: The interpretation of piezometric maps allowed to distinguish two hydrodynamic phases of the water; the first phase, during the monsoon, with a north-south flow. During this phase the influence of the pumping wells is not significant. On the contrary, the reduction of the water with the arrival of the dry season, shows a stronger influence on the wells. This is also noticeable by the reversal of the local hydraulic gradient inducing a change of the direction of groundwater flow.

The water balance calculations showed the significance of irrigation in the process of groundwater recharge. This dynamic can worsen the quality of the upstream water. A numerical model based on that information was developed in order to help to the overall understanding of the watershed and to help to conceptualize several scenarios.

Website or information on the web:

Project acronym/name: **Water Quality, Health and Agronomic Risks and Benefits Associated with "Wastewater" Irrigated Agricultu**re

Duration: 2005 - 2007

Framework: BMZ funding

Coordination/partnership: IWMI, Freiburg University, Applied Geography of the Tropics and Sub-tropics (APT), Freiburg. International Livestock Research Institute (ILRI), Hyderabad

Centre for Economic and Social Studies (CESS), Hyderabad and Environment Protection Training and Research Institute (EPTRI), Hyderabad

What was done: Framework of actors and interactions. Social and institutional map of the multiple actors (individuals and organizations) along the chain from wastewater source to end-use. GIS database of urban and periurban agriculture and wastewater irrigation. Evaluation of human health and agronomic risks from field to consumer. Economic valuation of the direct and indirect livelihood benefits as well as the health and adaptation-related costs of wastewater irrigation. Comprehensive assessment of tradeoffs, risks, costs and benefits at different levels along the chain from wastewater users to consumers of produce. Concrete, actionable risk mitigation recommendations (based on outputs 1-5 above).

Website or information on the web: Amerasinghe et al. 2008

5.1.3 Existing models

Groundwater model have been developed for the entire Musi basin by IWMI (Massuel et al. 2007) using MODFLOW, covering more than 11,000 Km^2. However, these models do not account for the micro-watersheds within it and therefore cannot be directly used for the setup of new models.

5.2 Models to be developed

5.2.1 Objectives of Saph Pani modelling work

Starting from the development of a flow and conservative transport model at the scale of the watershed, addressing hydrological interactions between the different water sources, this tool is supposed to evolve to assess the performance of the natural cycles of water, salt, nutrients and selected pollutants. This model will be used to optimise the performance of a combination of passive and engineered forms of treatment. Model type and modelling tools to be used are still to be defined.

5.3 Conceptual Model of the study site

Figure 22 provides a conceptual model of the the Kachwani Singaram Micro-Watershed in form of a schematic hydrogeological cross-section with the main flow components (Perrin *et al.*, 2011). Three main layers of the hard-rock aquifer have been distinguished: saprolite, fissured zone, fresh basement. The Musi river constitutes the downgradient boundary of the system draining groundwater as main contribution to base flow. It has been estimated that the impact of the irrigation canal on the flow pattern and overall water management is very limited.

Three zones can be divided depending on the used sources of irrigation water:

- irrigation water provided by groundwater pumping,
- irrigation water provided by mixing of groundwater and canal water,
- irrigation water provided by canal water.

Piezometric level fluctuations and vertical fluxes are controlled (and constrained) by the canal, the Musi river, the return flows from canal water irrigation in the downgradient part of the system. Therefore limited piezometric fluctuations exist in this part (moreover no groundwater pumping occurs). In contrast, in the upgradient part, the piezometric levels show significant seasonal fluctuations since natural recharge occurs mostly during monsoon and groundwater pumping occurs extensively during the dry season.

The entire downgradient part of the aquifer is most influenced by canal water return flows (i.e., waste water). The most upgradient part is not impacted by waste water (apart by local contamination due to farming activities or habitations) as natural recharge occurs. In between, the picture is more complex with migration of groundwater influenced by waste water in the “upgradient” part in function of the temporal variations in hydraulic heads: for instance during the dry season, hydraulic heads may become lower than heads controlled by canal irrigation as a result of pumping and groundwater influenced by waste water can migrate northwards.

Return flows from canal water constitutes the largest recharge flux at the basin scale and has therefore a significant impact on both the hydrodynamics and the quality of the aquifer. Future development of groundwater pumping upgradient may induce a northwards migration of the groundwater influenced by wastewater.

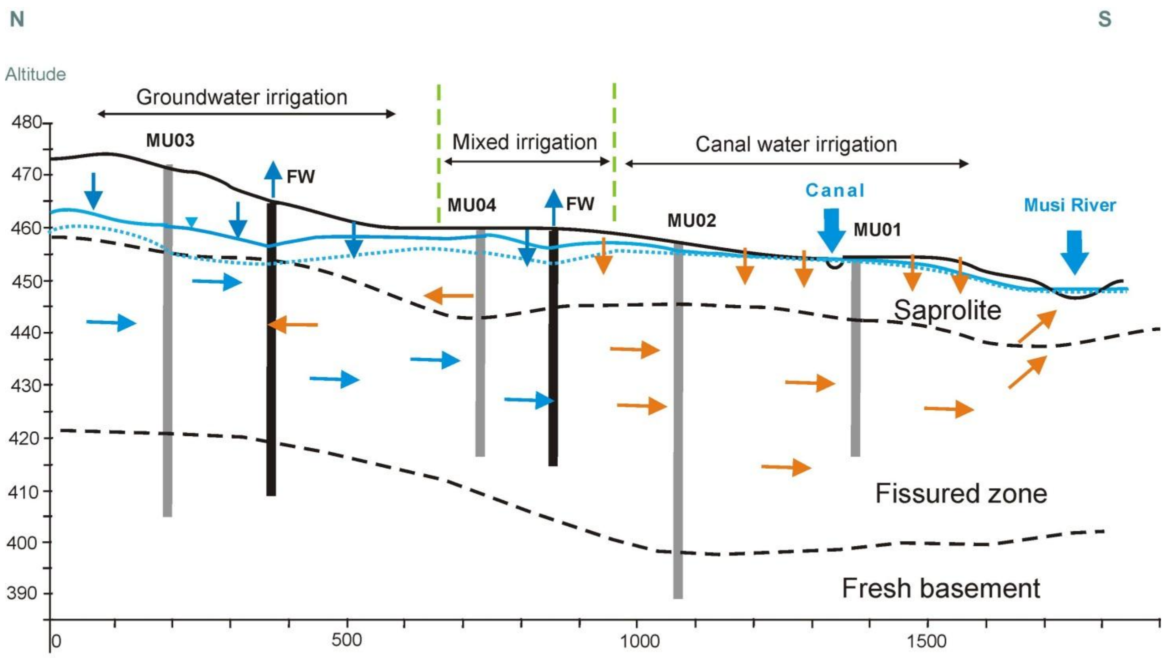

Figure 22 : Conceptual model of the study area hydrogeology: vertical arrows indicates irrigation return flows (blue for groundwater irrigation, orange for canal water irrigation) ; sub-horizontal arrows indicate groundwater flow direction (blue for fresh groundwater, orange for groundwater influenced by canal water return flows). The plain blue line is the piezometric level after monsoon recharge and the dashed blue line the piezometric level during the dry season. FW= farmer irrigation wells. Inferred transport processes are purely advective in this conceptualisation (Perrin *et al.*, 2011).

5.4 Status of numerical modelling at M12

The start of Task 5.3 "Modelling approach of Musi river wetland treatment/SAT site" is scheduled for M12

5.5 Site-specific literature list

5.5.1 Publications (journals, conferences….)

Amerasinghe, A., P. Weckenbrock, R. Simmons, S. Acharya, and M. Blummel (2008). An atlas of water quality, health and agronomic risks and benefits associated with "wastewater" irrigated agriculture an atlas of water quality and agronomic risk and benefits associated with "wastewater" irrigated agriculture. a study from the banks of the musi river, india. Published online: http://www.freidok.unifreiburg.de/volltexte/6963/

Ensink, J. H. J., C. A. Scott, S. Brooker, and S. Cairncross (2009). Sewage disposal in the musi-river, india: water quality remediation through irrigation infrastructure. Irrigation and Drainage Systems.

Massuel, S., Biju George, Anju Gaur, Rajesh Nune. (2007). Groundwater Modeling for Sustainable Resource Management in the Musi Catchment, India. MODSIM07 Conference Proceedings. p. 1429-1435 http://www.mssanz.org.au/MODSIM07/papers/23_s31/Groundwater_s31_Massuel_.pdf

McCartney M., Scott C., Ensink J., Jiang B. and Biggs T. W., (2008). Salinity implications of wastewater irrigation in the Musi River catchment in India. Cey. J. Sci. (Bio. Sci.) 37 (1): 49-59

J. Perrin, S. Ahmed, L. Dinis, V. Aellen, P. Amerasinghe, P. Pavelic, R. Schmitt (2011). Groundwater processes in a micro-watershed influenced by wastewater irrigation, peri-urban Hyderabad. Hyderabad, National Geophysical Research Institute (NGRI), Bureau de recherches géologiques et minières (BRGM), International Water Management Institute (IWMI). IFCGR/IWMI 2009 – 2010. Pp 54

Schmitt, R. (2010). Wastewater reuse in Indian peri-urban agriculture Assessment of irrigation practices in a small, peri-urban catchment in Hyderabad, Andhra Pradesh, India: Mémoire, Swiss Federal Institute of Technology. Pp 93

Biggs, T. W., and B. Jiang. (2009). Soil Salinity and Exchangeable Cations in a Wastewater Irrigated Area, India. J Environ Qual 38 (3):887-896.

Van Rooijen D.J., H. Turral, T.W. Biggs, (2005), Sponge city: Water balance of mega-city water use and wastewater use in Hyderabad, India, Irrigation and drainage, 54, S81-S91.

Aellen, V. (2011). Etude Hydrogeologique Et Modelisation D'un Bassin Versant En Inde Master En Hydrogéologie Et Géothermie Spécialisation En Hydrogeology Centre D'hydrogéologie Et Géothermie Université De Neuchâte. Pp 77

6 Maheshwaram site

6.1 Site specific background knowledge

6.1.1 Synthetic site description

One of the main experimental watersheds relevant for MAR studies in WP2 is located around the town of Maheshwaram (Figure 23). With a total area of 54 km^2, it is located in a semi-arid hard-rock context typical for the entire region where the saprolite layer (10-20 m thick) is usually unsaturated. It is a watershed with a high density of groundwater production wells (>700) mostly for paddy irrigation; changes in land use have occurred since 2006, the new Hyderabad international airport being located less than 10 km away. It is expected to become a peri-urban area within the coming years as significant housing projects are planned. MAR has been implemented throughout the watershed in the form of percolation tanks, check dams, defunct dug wells, etc. over the last decade.

Intensive groundwater exploitation for irrigation has resulted in aquifer over-exploitation and deterioration of groundwater quality (fluoride above maximum permissible limit of 1.5 mg/L, salinisation and agricultural inputs). MAR is an attractive concept for groundwater augmentation and enhanced groundwater quality nearby wells exploited for domestic uses. The objective of the tasks in WP2 for the case study site in Maheshwaram is to investigate the potential of percolation tanks and defunct dug wells to enhance recharge and groundwater quality in the underlying overexploited hard-rock aquifer by implementing a sophisticated monitoring strategy for groundwater levels and quality, conducting hydrogeochemical analyses and investigating the hydrodynamics with the support of a conceptual groundwater balance model developed in cooperation with WP5.

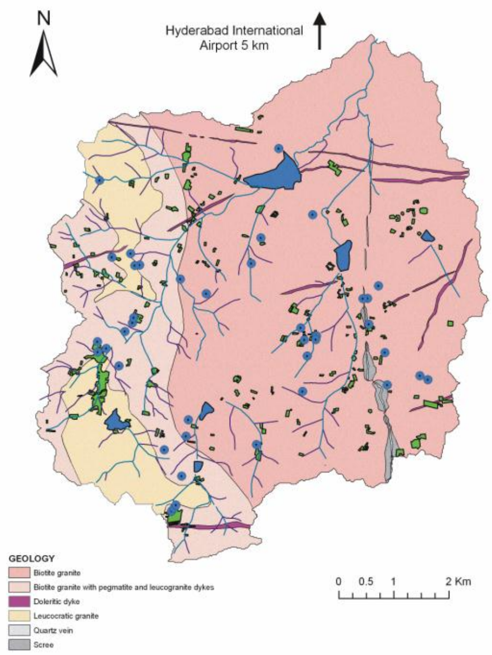

Figure 23 Geological map of Maheshwaram watershed. Main MAR (percolation tanks and defunct dugwells) structures are indicated in blue Green areas are irrigated paddy fields.

6.1.2 Previous projects

Project acronym/name: MOHINI Project: Integrated MOdelling of Hard rock aquifers : Vulnerability to global change of anthropogenic origin

Duration: from 2008 to 2011

Framework: ANR funding

Coordination/partnership: BRGM / NGRI, Géosciences Rennes, Géosciences Montpellier, ITASCA, Strasbourg

What was done: At Maheshwaram, groundwater is the main source of drinking water supply and is characterized by a high variability of fluoride concentrations often exceeding the drinking water limit. During the course of the MOHINI project, whereas fluorosis has never been detected before, a study of the effectiveness of dental fluorosis prevalence in the school age (6-18 years old) population of Maheshwaram has revealed that 89 % of the 501 children surveyed exhibited various degree of dental fluorosis, with about 6 % presenting a severe dental fluorosis. At the same time, geochemical investigations allowed a better understanding of the processes responsible for fluoride accumulation. These investigations led to a geochemical model tested for various conditions corresponding to 3 evolution scenarios by the year 2014 in agreement with the 2020 vision of Andhra Pradesh government.

Project acronym/name: QUANTIFICATION OF HYDROLOGICAL FLUXES IN IRRIGATED LANDS USING ISOTOPES FOR IMPORVED WATER USE EFFICIENCY

Duration: from 2009 to 2011

Framework: AIEA Funding

Coordination/partnership: BRGM/NGRI

What was done: Paddy field hydrodynamics was investigated by combining different methods: water fluxes direct monitoring, sampling of conservative tracers (chloride, stable isotopes) during one hydrological year, a conservative tracer (Br) test. The results bring a refined conceptual model of irrigation return flows and a quantification of the water fluxes at paddy field scale : infiltration, evaporation, transpiration.

Website or information on the web:

***Project acronym/name*:** Setting-up the Maheshwaram experimental watershed

Duration: since 2000

Framework: BRGM, NGRI

Coordination/partnership: APGWD, BRGM, NGRI

What was done: Over twenty piezometers were drilled for a monthly piezometric monitoring and geological description. Geological mapping was carried out supported by geophysical measurements (VES, resistivity logging, etc.) and maps of weathering profile thicknesses were performed. Hydraulic tests (slug tests, flowmeter, aquifer tests) were performed both on the regular weathered granite (Maréchal et al. 2004) and on quartz reefs (Dewandel et al. 2011) for determination of aquifer hydrodynamic properties.

A meteorological station was set up in 2000 for rainfall, evaporation, wind speed and temperature measurements. Since 2001, seasonal piezometric campaigns have been carried out on over 100 piezometers and abandoned irrigation wells. A well inventory was carried out in 2002. These data were used to compute the groundwater balance at watershed scale. An irregular number of piezometers were equipped with automatic water level recorders. Groundwater chemistry monitoring (major ions, some traces, stable isotopes) is carried out since 2006 on over 30 wells. A preliminary study on artificial recharge using a dug well was carried out in 2005-2006 at the “recharge site” with implementation of piezometers, derivation of runoff to a defunct dug well, and water level monitoring in the dug well.

Website or information on the web : www.ifcgr.net

6.1.3 Existing models

No effective projects have been conducted at the scale of the modelling sites (dugwell and percolation tanks) however a complete information set is available at the watershed scale.

- Geological conceptual model (Dewandel et al 2006)

- Global water balance and Decision Support Tool (DST) for water resources management (REF: Maréchal et al. 2006, Dewandel et al 2007, 2011)
- Solute recycling model at watershed scale (Perrin et al. 2011a)
- Geochemical model for solute recycling at watershed scale (Pettenati et al. accepted)

6.2 Models to be developed

6.2.1 Objectives of Saph Pani modelling work

Maheshwaram basin catchment has been investigated through numerous studies (geology, hydrogeology, GIS, geochemistry…) since the two last decades. Many data have been obtained during these studies on the entire extent of the watershed. The aim of the modelling within the project is, starting from the available data, to:

- understand the capacity of artificial recharge to enhance/improve the quantitative management of the aquifer. This objective requires the conceptualization of a hydrogeological model at the scale of the Maheshwaram watershed (54 km²). This conceptual model is a prerequisite for designing a hydrogeological 3D meshed model representing the initial state of the watershed (before artificial recharge site implementation). Evolution scenarios will be conceived for evaluating artificial recharge impact on aquifer flow (quantitative). *NB.: This option is dedicated to hydrogeological study only and do not comprise any coupled processes like reactive transfer*.
- describe and quantify the water-rock interactions processes during the recharge and the corresponding impact, at the global scale of the watershed, on water quality. This study will be conducted in parallel with the hydrogeological modelling. Results of hydrogeological models including scenarios of recharge can be used in terms of mass water budget to evaluate the beneficial (or adverse) effect of recharge onto soil salinization and fluoride accumulation in the special case of Maheshwaram aquifer. The geochemical model of solute recycling (Pettenati et al., 2012, *accepted*) will be updated with these new data.

6.2.2 Target groups, potential endusers of SAPH PANI models

- In the case of the hydrogeological model at the watershed scale, it is expected that the water companies themselves can use the model.
- For the geochemical model, the utilisation is limited to researchers and experts in order to evaluate the enhancement of water quality in the case of artificial recharge.

6.2.3 Model type

Time scale, steady-state or transient state: both

Spatial scale: for hydrogeological modelling the scale is 54km² (watershed area)

FE, FD, nesting…:-

1D-3D: 2D radial or 3D for hydrogeological modelling and 1D for geochemical modelling

Flow and transport: both

(*Geo)chemical model, reactive flow:* 1D reactive transport model

6.2.4 Modeling tools to be used

Tools for data management: EXCEL, ARCGIS

Tools for modelling: MARTHE will be used for or 3D for hydrogeological modelling and PHREEQC for 1D geochemical modelling

Will existing tools be used as-is or is development planned within the project? MARTHE development integrating local surface water accumulation into the tank during monsoon and percolation to groundwater. Possibility to develop the coupled version of MARTHE with PHREEQC for reactive transfer flow model.

6.2.5 Modeling tasks and responsible partners

IFCGR – BRGM/NGRI: on site data collection – Conceptual model Construction/participation

6.3 Conceptual Model of the study site

Tummulur Tank Scale

The conceptual model of the study site needs to include the spatiotemporal evolution of the tank linked to topographic, strong rainfalls of monsoon, evapotranspiration, infiltration, runoff and groundwater dynamic (Figure 24) while respecting the hydraulic mass balance (Figure 25). Rainfall is stored at surface where artificial topographic modifications prevent superficial water runoff during the monsoon season. One part of the water intfiltrates into the soil and deeper, toward groundwater and another part is evaporated during monsoon and dry periods.

Before evaluating the quantitative impact of artificial recharge through a larger number of tanks built in the same way as Tummulur tank on aquifer flow this conceptual model has to be tested on Tummulur tank case through a numerical hydrogeological MARTHE model.

Maheshwaram Watershed Scale

The work attempts the updating of an existing numerical MARTHE model (Petrelluzzi, 2004) representing the experimental watershed with recent knowledge from studies of the hydrogeological system (Dewandel et al., 2010; Negrel et al., 2011; Perrin et al., 2011b; Dewandel et al., 2011; Dewandel et al., 2012). The main purpose of this exercise is to develop a hydrogeological 3D meshed model representing the initial state of the watershed (before artificial recharge site implementation) as future decision-making tool.

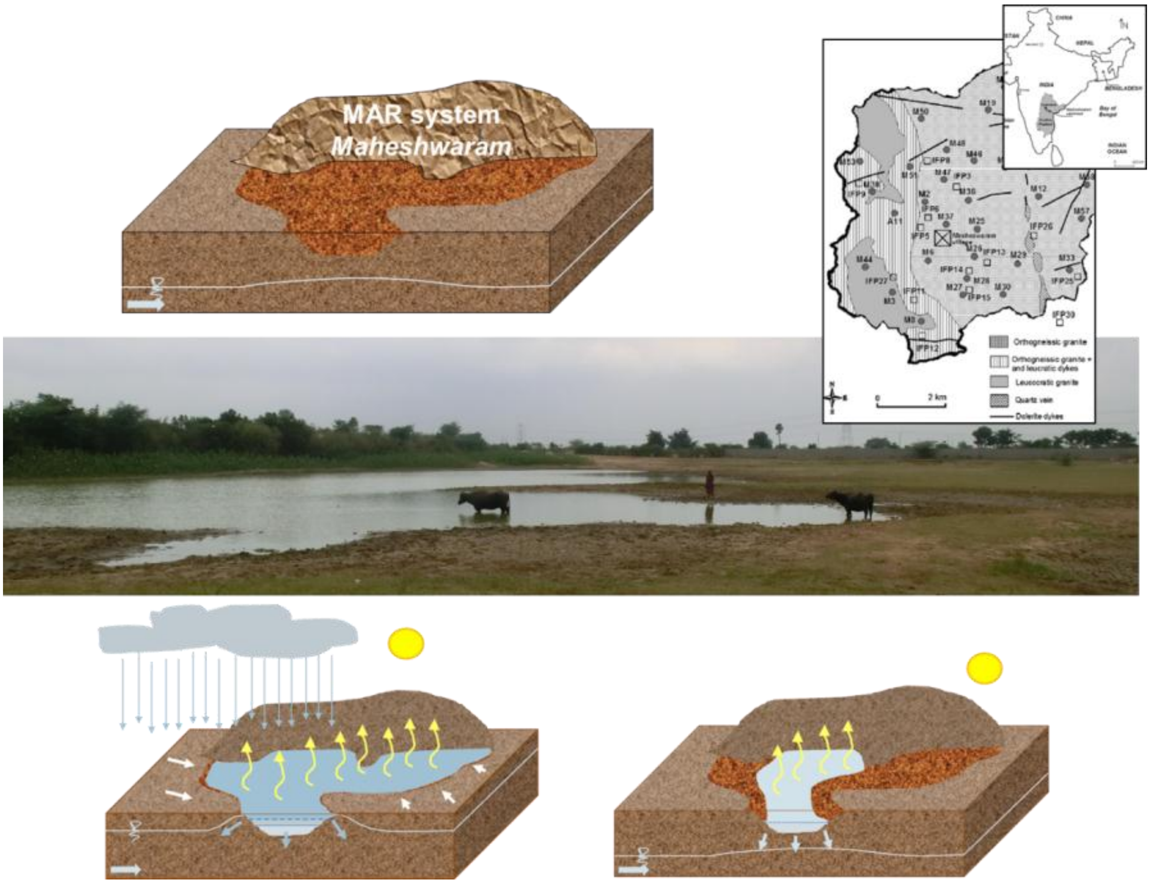

Figure 24: Conceptual model of spatiotemporal evolution of the Tummulur tank studied in Mahesharam

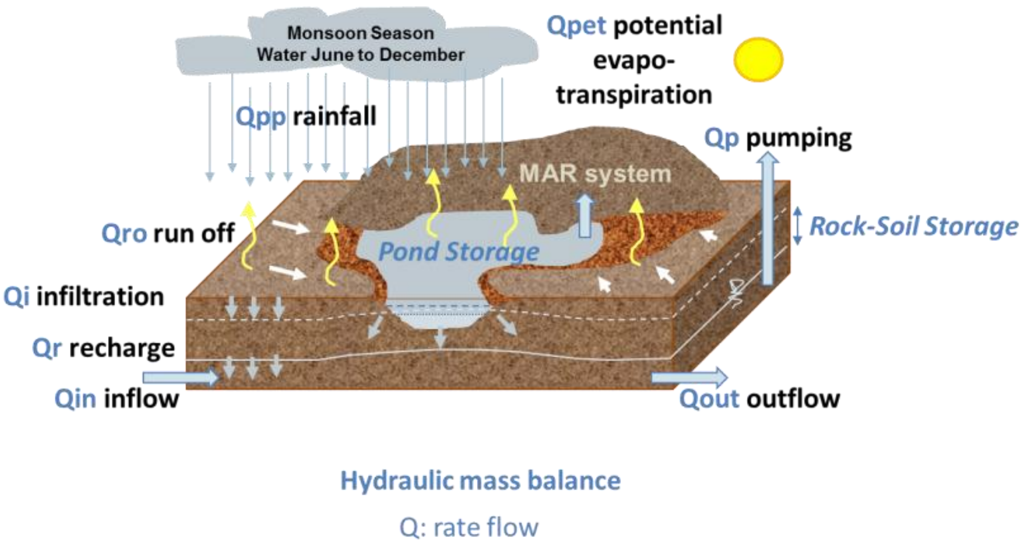

Figure 25: Conceptual model of Tummulur tank studied in Mahesharam in accordance with hydraulic balance

To describe the impact on water quality during the recharge at the global scale of the watershed, a first step is to quantify the water-rock interaction processes on a 1D vertical geochemical reactive column adapted from the geochemical model of solute recycling (Pettenati et al., 2012, accepted) linking hydrodynamics calculated by MARTHE (infiltration, potential evapotranspiration, unsaturated flow) and geochemical reactions calculated by PHREEQC (Figure 26).

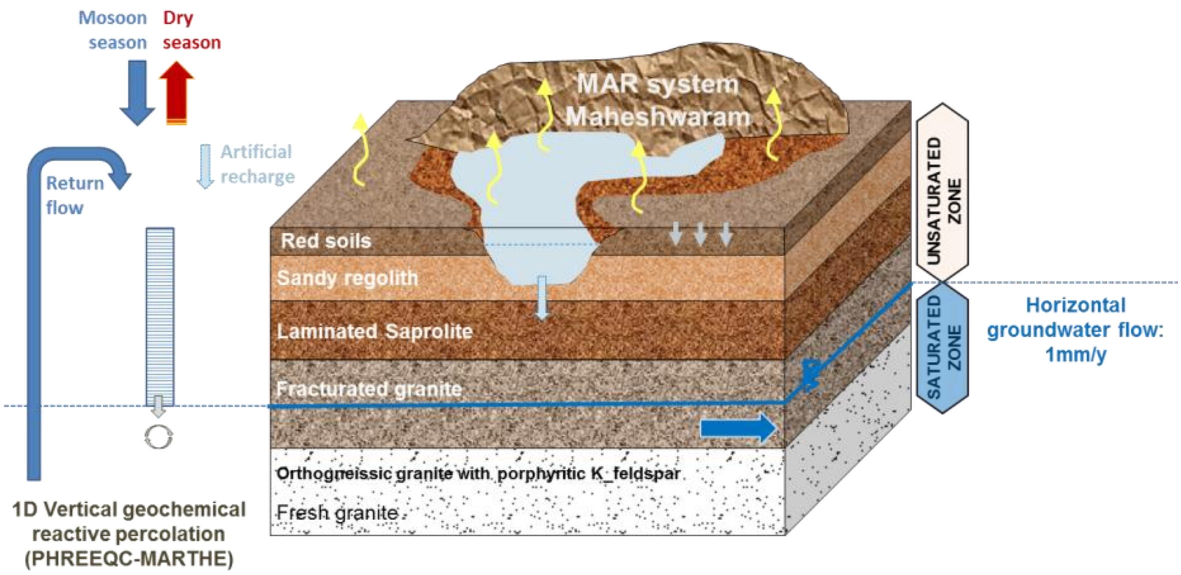

Figure 26: Conceptual model of water-rock interactions processes linked to hydrodynamics.

The results, including scenarios of recharge, can be interpreted in terms of mass balance of solute flow through the watershed-scale 3D flow-transport model to evaluate the beneficial, neutral or adverse effect of recharge onto soil salinization and fluoride accumulation in the special case of Maheshwaram aquifer.

6.4 Status of numerical modelling at M12

- Numerical model development of spatiotemporal evolution of Tummulur tank: governing equation development and implementation into MARTHE code in progress,
- 3D numerical model of Maheshwaram watershed: acquisition and evaluation of knowledge dedicated to MARTHE modelling in progress,
- 1D vertical geochemical reactive percolation (MARTHE-PHREEQC): review of water quality and geochemical processes at watershed scale in progress. MARTHE-PHREEQC linking not started.

6.5 Site-specific literature list

6.5.1 Publications (journals, conferences….)

Chandra, S., S. Ahmed, et al. (2008). "Estimation of hard rock aquifers hydraulic conductivity from geoelectrical measurements: A theoretical development with field application." Journal of Hydrology 357(3-4): 218-227.

de Condappa, D., S. Galle, et al. (2008). "Bimodal zone of the soil textural triangle: Common in tropical and subtropical regions." Soil Science Society of America Journal 72(1): 33-40.

Dewandel B., J.C. Maréchal, O. Bour, B. Ladouche, S. Ahmed, S. Chandra, H. Pauwels (2012) "Upscaling and regionalizing hydraulic conductivity and effective porosity at watershed scale in deeply weathered crystalline aquifers." Journal of Hydrology, (416–417): 83–97.

Dewandel, B., P. Lachassagne, F.K. Zaidi, S. Chandra (2011) "A conceptual hydrodynamic model of a geological discontinuity in hard rock aquifers: example of a quartz reef in granitic terrain in South India" Journal of Hydrology 405): 474–487.

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