Results of background work and data integration of MAR systems for an Integrated Water Resources Management

TECHNEAU

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Introduction

The use of groundwater for public water supply and irrigation has many benefits for water suppliers as well as for consumers. Over the last decades availability and consumption of this valuable resource has increased worldwide along with technical progress, but it has often been ignored that any abstraction of groundwater is an intervention in the balance of the natural water cycle.

Managed aquifer recharge (MAR) present the double interest :
1. to be a possible technical answer to over-exploitation of groundwater reservoirs and can contribute to water resource preservation and possibly reuse
2. to provide a natural cleaning step to pre-treat surface water for drinking water supply, and therefore could contribute to reduce the need for highly sophisticated treatment methods which are cost intensive in installation and also in maintenance.

In many parts of the world, such as low income countries, MAR offers the possibility to profit from the storage and purification capacity of natural soil/rock and to guarantee a sustainable management of groundwater.

River bank filtration is an ancient and widely used method that currently provides water to a large number of population in EU (45% of Hungarian water supply, 16% of German water supply, 5% of The Netherland water supply). River bank filtration relies on natural conditions to operate efficiently and allow to produce a quality of water which, in some cases, doesn't required further treatment before distribution (such as in Berlin). There are now many evidences that global environmental conditions are progressively changing and may impact existing water supply scheme by bank filtration. The extensive study of bank filtration systems in different environmental settings (such as in India with higher temperature, different surface water quality, systems subject to monsoons and flooding ...) will allow apprehending the limitation that current bank filtration systems may face, and highlight the possible need for adaptive strategies.

The aim of this report is to document work performed within the first 6 months since the start of WP 5.2 of TECHNEAU integrated project and to give an overview of the results and future planning. This includes detailed regional investigations, field studies and laboratory work performed in collaboration between the KompetenzZentrum Wasser Berlin gGmbH (KWB), the Indian Institute of Technology in Delhi (IIT) and the Freie Universität Berlin (FUB).

Preliminary studies at potential sites in different parts of the world were performed prior to the TECHNEAU Project with the aim to investigate their suitability for RBF and thus to allow for deeper investigation within TECHNEAU. These preliminary studies were carried out in the cities

Kaliningrad (Russia), Recife (Brazil) and New Dehli (India), and were funded by Veolia Water.

In Recife (Brazil), the investigation performed by the FUB showed that both hydrogelogical data and model results indicate that the area is not suitable for the production of drinking water by RBF in sufficient amounts due an unfavorable hydrogeological conditions (too low transmissivity of the target aquifer because of the low content of sand in the samples and the scarce distribution of sandy sediments). At this point further investigations were stopped since no alternative field site area was found.

In Kalingrad, water quality data that was gained in the preliminary study from the field site and will be compared with the data gained from investigations in Delhi and Berlin.

In Delhi, India, the appropriate conditions, as well as the establishment of a valuable collaboration with the IIT, has lead to the implementation of three different field sites (in three different conditions). The activity performed within the techneau framework and included (i) the integration of existing information and literature on local climate, geology and water supply system, (ii) the detailed investigation about the local hydrogeology and ground and surface water quality and (iii) the development of a GIS (Geo Information System).

Results

In agreement with local authorities, three different field sites were selected in the territory of Delhi, representing distinctly different environmental conditions within the district. According to local conditions, a net of 17 groundwater observation points (piezometers) has been designed and installed on each of the field sites. A description of local geology, including stratigraphical charts has been elaborated, based on the evaluation of information obtained during the drilling and from analysis of sediment samples. A strategy for monitoring of water level and water sampling analysis has been developed, and monthly field campaigns have been carried out. Water samples have been analyzed, considering a broad variety of parameters including major chemical contents, trace substances and pathogens. Hydraulic tests have been conducted to obtain aquifer properties in order to estimate travel velocities during underground passage.

1. Introduction

1.1. Motivation

Depending on the quality achieved with MAR, adjusted conventional treatment can be added matching the required water quality. Common MAR-techniques include riverbank filtration (RBF), Aquifer storage and Recovery (ASR), deep well injection and ponded infiltration. As the installation of these techniques requires detailed hydrogeological pre-investigation, initial investigation costs are relatively high. On the long run however, costs for operation and maintenance may be rather small compared to other techniques, since the level of technical support and energy demand are relatively low (Table 1.1).

Table 1.1 Factors affecting technology choice for water supply (after Dillon et al., 2005b)

Method	Typical devolution/scale (m^3/year)	Typical unit cost US$/$m^3$	Limits	Relative investigation costs	Relative technical knowledge needed	Relative regulation difficulty
Purifying tablets/filters	Family: $10\text{-}10^2$	<1	Treats only pathogens	-	*	*
Rainwater tanks	Family: $10^2\text{-}10^3$	10	Fails in drought	*	**	*
MAR	Village/town: $10^3\text{-}10^6$	1-10	Needs aquifer	****	***	***
Dam and treatment plant	Region: $10^7\text{-}10^9$	10-100	Needs dam site	*****	****	***
Desalination	Town/region: $10^3\text{-}10^7$	1-100	Needs power, brine discharge	***	****	*

River Bank Filtration (RBF) is an established technique to enhance aquifer recharge from surface water by the abstraction of groundwater in the vicinity of a natural surface water. During pumping the surface water is forced to infiltrate into the gound and starts to interact with ambient soil matrix. Before the infiltrated water (bank filtrate) reaches the well, it is modified by a series of physical, chemical and biological processes. Purification capacity during bank filtration strongly depends on environmental conditions, well design and well operation.

Integrating MAR, especially RBF and ponded infiltration, as a “natural” treatment step into the water treatment chain is common practice in Europe. In the city of Berlin for example, bank filtration has a tradition of more than 100 years and today provides 70% of the drinking water production. Optimisation of installation, operation and integration of such systems in Europe developed step-by-step and co-evolved with (i) the improvement of the analytical techniques for water quality parameters, (ii) the progressively better understanding of site-specific hydrogeology, geochemistry and flow process, and (iii) the development of other treatment methods. Until now, MAR is carefully integrated into the overall treatment chain and still an essential part of sustainable integrated water management in many European cities.

Meanwhile in most of the developing and newly industrializing countries RBF as low-cost option for increasing the security and quality of water supplies has not yet been recognized by the responsible authorities. In many of these nations the development of affordable solutions to improve water supply urges more than ever: The United Nations Development Program (UNDP) Annual Report 2006 points out how the deficits in water and sanitation and associated ill health undermine productivity and economic growth, reinforcing the deep inequalities that characterize current patterns of globalization and trapping vulnerable households in cycles of poverty. Especially in the urban environments of developing countries and new industrialised countries a threatening extent of mismanagement of resources, growing competition for the use of fresh water and degradation of sources is being observed. The situation is getting worse by the explosive growth of urbanization and the formation of mega-cities through massive migration to the cities provoking an uncontrolled, unplanned expansion (UNESCO/IHP 2006). The UNDP report 2006 warns that competition for water will intensify in the decades ahead so that the consequences may cause severe conflicts on a national scale and even hold the potential for cross-border tensions in water-stressed regions.

To achieve "universal access to water and sanitation" the UNDP report 2006 recommends enhancing the effectiveness of international cooperation and concrete action. The European Union has approached the task by launching a water initiative with the general objective to strengthen institutional capacity at regional, national and local level, by providing expertise and promoting good practice, improved partnerships for sharing technology, information, research and knowledge and by raising awareness (EUWI 2004). It is important though, to learn from the mistakes from the past century, when many of the so called "development aid" projects have been introducing groundwater exploitation even in arid and semiarid areas. At the same time governments of many developing countries and new industrialised countries subsidized implementation and operation of groundwater pumping for rural development and poverty reduction programmes, with the consequence of uncontrolled over-exploitation of groundwater. In large regions of South and Southeast Asia for example, a groundwater boom over the last decades has triggered groundwater level declines, wells running dry, rising energy use and pumping costs, weakening drought protection, salinity ingress and even health hazards due to the mobilization of toxicants (Sharma et al., 2006). Far-reaching social as well as environmental consequences of depletion leave massive after-effects on all, however more on the poor than on the rich (Shah et al., 2000).

In those regions where a sustainable management of groundwater resources has failed and where the treatment of polluted surface water requires high technological and financial effort, many international, national and local organisations agree that MAR as part of an integrated water resources management has great potential to increase the security and quality of water supplies (Dillon 2005a). Examples given by Sandhu et al. (2006) and Dillon (2002) illustrate direct benefits expected by integrating MAR as a low-cost technology in to the water treatment chain in developing countries and new industrialised countries:

- Implementing new techniques to ensure affordable access to safe water by means of bank filtration can help to reduce poverty and improve livelihood. The society may also benefit from reduced medical costs and an improved productivity of the consumer.
- By utilizing natural degradation capacity for pathogens during infiltration MAR can help to reduce use of chemical disinfectants. Accumulation of disinfection by-products in drinking water and in the environment as it is currently being observed in different parts of the world can be prevented as less disinfection is necessary.
- By an optimal exploitation of bank filtrate the man made decline of groundwater level can be countered. Controlled drawdown and stabilized water levels help to:
    - Reduce energy consumption of pumping cost and
    - Improve reliability of source-water, for public water supply (→ better basis of planning) and irrigation (→ increased yields).
    - Improve distributive equity because higher water levels simplify access for everyone.
    - Minimize the risk of aquifer contamination by intrusion of seawater in coastal areas or up-coning of naturally occurring saline groundwater.
- Using the physical storage capacity of an aquifer by infiltrating surface water into the ground can help to relieve seasonal changes in surface water availability. Time delay and mixing on the way from the source to the consumer reduces vulnerability to draughts or variations in precipitation.
- When MAR acts as a part of a multi barrier system for drinking water supply the risk of spontaneously occurring hazards from unpredicted events like spills or terrorists attacks can be minimized.
- Compared to conventional treatment methods, bank filtration can be regarded as a relatively economic technique, serving as an asset to water suppliers by way of capital cost reduction through lower maintenance and the advantages mentioned above.

1.2. Objectives

According to the proposal the main objectives of the investigations in WP5.2 are to:

- Identify MAR as an effective (pre-) treatment method as a part of multi-barrier system to enable sustainable and safe integrated water resources management for developing countries and new industrialised countries

- Integrate extremely diverging environmental conditions into the existing knowledge for a better transferability of MAR technology
- Develop an operational system of combined treatment processes (MAR+post treatment)
- Develop guidelines (in form of a guidance tool) for an optimal implementation and operation of MAR systems and to select proper post treatment
- Demonstrate and train end-user and local communities in construction, and maintenance of MAR systems as well as sustainable resource protection

N.B.: On the basis of the first investigations of WP5.2 and under consideration of results from WA1 on trends and adaptive strategies, and WA2 on water treatment technologies, the original objectives of the WP (defined in 2005) are currently being updated by the WP and will be submitted to the techneau board for approval.

2. Preliminary investigations and strategy

As the effectiveness of MAR strongly depends on a series of local boundary conditions, the transferability of the process understanding is not yet given (despite of all practical knowledge and scientifically investigations). For the optimization of existing sites (in terms of preparation for future scenarios like the consequences of global warming) or for the planning of new sites, further site-specific investigations and modelling studies are required. As MAR has particularly been practised and investigated in Eastern and Central Europe (commonly as RBF and ponded infiltration), there still is a lack of research from other parts of the world.

One of the major missions of KWB and FUB not only within TECHNEAU is to produce an integrated understanding of MAR for diverging environmental and socio-economic conditions, thus creating transferable know-how to enable low-cost sustainable and safe water resources management in developing countries and new industrialised countries.

Preliminary studies at potential sites in different parts of the world were performed prior to the TECHNEAU Project with the aim to investigate their suitability for RBF and thus to allow for deeper investigation within TECHNEAU. These preliminary studies were carried out in the cities Kaliningrad (Russia), Recife (Brazil) and New Dehli (India), and were funded by Veolia Water and KWB.

2.1. Outcomes of preliminary studies and supplemental activities

2.1.1. Delhi

The preliminary studies revealed that the field-site conditions in the Indian Capital, New Delhi are most suitable for RBF. Thus, investigations in WP5.2 focus on the Delhi field sites. In the following sections we report the results of the first 6 month of investigation at the Delhi field sites, including the results of the preliminary study.

2.1.2. Kaliningrad

No further field site investigations are planned in Kaliningrad. However, water quality data that was gained in the preliminary study from the Kaliningrad field site will be compared with the data gained from investigations in Delhi and Berlin. This task, which also might include basic reactive transport modeling to constrain degradation rates constants, will be covered completely with KWB internal funds.

2.1.3. Brazil

The preliminary study was carried out in a province of the north-eastern region of Brazil, in Recife at the coast of the Atlantic ocean. The province capital Pernambuco exhibits a population of about 3 Mio. inhabitants and is the largest and most important city of the region. The drinking water supply of about 300 Mm^3/a is managed by the use of treated (chlorinated) surface water from 12 reservoir lakes.
In the late 1990´s a case of 26 fatal poisonings caused by algae toxins occurred in Recife. At this time local authorities began to rethink their current water supply chain and a multi barrier system was intended to construct.

Two main aquifer types exist in the region: a) unconsolidated, porous aquifers of young (quaternary to tertiary) sediments at the coastline and in the alluvial plains of the rivers. b) fractured, crystalline rocks with very low permeability. Saltwater intrusion is the main problem in the flat shallow plains along the shoreline of the Atlantic Sea. The influence of the saltwater intrusion is observed up to 20 km from the coastline in the hinterland. The basement and crystalline hills are about 20 km from the coastline and are generally build up of volcanic rocks which are considered to be aquicludes. Only a few alluvial plains exist between the crystalline hills. From these only a few were big enough and have no saltwater influence and therefore are considered to be a potentially field site for the production of drinking water by RBF. The lithological composition and the thickness of the young alluvial sediments were widely unknown.

To investigate the feasibility of RBF the hydraulic conductivity and the thickness of the aquifer are of main interest. Hydraulic conductivity can be calculated from the grain size distribution of the sediments. Drilling campaigns were carried out to investigate the hydraulic properties of the aquifers. Eleven boreholes have been drilled in the alluvial plains of the Ipojuca river and another 3 at the Pirapama river. All drillings were performed up to the depth were crystalline basement rock was reached. During the drillings sediment samples at every meter and at every change of the sedimental composition were analysed. The sediment samples were examined for the grain size distribution and the hydraulic conductivities were calculated. The basement was found in depth between 9 and 23 m below ground surface. From the evaluated data a hydrogeological structure model was created and based on that numerical hydraulic modelling was carried out.

Both hydrogelogical data and model results indicate that the area is not suitable for the production of drinking water by RBF in sufficient amounts due an unfavorable hydrogeological conditions (too low transmissivity of the target aquifer because of the low content of sand in the samples and the scarce distribution of sandy sediments). At this point further investigations were stopped since no alternative field site area was found. Thus, an extension of the WP5.2 program regarding time schedule and budget for further investigations in Brazil is no longer considered.

2.2. Additional field sites

A potential inclusion of additional field sites in the original working program of WP5.2 will be discussed with the leader of WA 5. However, it is worthwhile to note that in Delhi alone, three field sites were selected for further investigation. These sites cover diverse environmental conditions with respect to surface water quality and hydrogeology.

2.3. Supplemental activities

Aside from the TECHNEAU project, KWB carried out further activities towards the creation of transferable know-how of MAR by supporting RBF feasibility studies in developing countries and new industrialised countries within in the framework of the UNSESCO-IHE masters programs (see BOSUBEN, 2007). In these studies, initial steps have been made towards (i) transferring existing knowledge on RBF to developing countries and new industrialised countries and (ii) the development of guidelines to implement RBF in the water treatment chain. In this context the NASRI-Bankfiltration Simulator (KWB, 2007) as one of the major outcomes of the NASRI-Project (Natural and Artificial Systems for Recharge and Infiltration, 2002-2005) has been applied and tested. The results of these research activities are additives to be incorporated into the work of WP5.2.

2.4. Strategy for Delhi (preliminary study and first 6 months of activity)

Activities were carried out at three suitable field sites in Delhi and included (i) integration of existing information and literature on local climate, geology and water supply system, (ii) detailed investigation about the local hydrogeology and ground and surface water quality and (iii) development of a GIS (Geo Information System).

The GIS is used (i) to estimate spatial and temporal distribution of geographical and geological features like extent and course of rivers, land-use pattern, digital elevation model, (ii) to calculate the areal extent of the Yamuna watershed and (iii) to layout maps for different needs.

The exact locations of the field sites were selected during the preliminary study and drilling campaigns were carried out at each site between November 2006 and February 2007. A large set of piezometers were installed for groundwater sampling and water level monitoring (see Chapter 4).

At this first stage of the project the basis for flow, transport and reactive models was achieved by analysing the hydrogeological, hydraulic and hydrogeochemical conditions at the field sites. Therefore, pumping tests were carried out in order to estimate aquifer parameters like transmissivity, storage coefficient and anisotropy factor. Since December 2006 monthly sampling campaigns were carried out to detect seasonal changes of hydraulic and hydrochemical parameters through the annual cycle. The hydraulic changes are monitored by several level logger units.

3. State of the art (RBF)

The quality of raw water obtained by bank filtration depends strongly upon a series of factors, among them the quality of surface waters, the hydrological and (hydro-) geochemical conditions of the subsurface and the residence time of the bank filtrate. Moreover, the river sediment may significantly influence the groundwater quality. Physical processes (filtration, mixing. dilution), physico-chemical processes (dissolution and precipitation, ion-exchange and sorption) and biological processes (transformation, oxidation and mineralization, reduction) alter the quality of the former surface water during passage of the subsurface (Figure 3.1). In the following we give a brief overview about state-of-art research on riverbank filtration.

Different aspects of RBF have been subject of scientific investigations in many parts of the world over the last 30 years, especially in Europe (SONTHEIMER & NISSING 1977, KÜHN & MÜLLER 2000, SCHMIDT et al 2003) and the United States (WEISS et al 2002, C. RAY (ed.) et al 2002).

Main concern in planning and constructing of new RBF sites is the design and setup with respect to the hydrogeology, the surface water conditions and the purposes of the water abstraction. GRISCHEK 2002 describes general procedures in the planning and designing of RBF sites since most of the knowledge is based on personal experiences. Obviously it is important to be sure that the surface water is in hydraulic contact with the adjacent aquifer.

An important parameter is the formation of a clogging layer at the river bed that causes a reduction in hydraulic conductivity but, on the other hand increases the absorption and degradation potential. SCHUBERT 2002 reports of a temporal and spatial changing of the clogging layer within a highly dynamic hydrology. The design of a RBF site should be balanced between the volume of the abstracted bank filtrate and the water quality due to attenuation and mixing during the underground passage. GRISCHEK 2002 also emphasis that the design and setup of RBF sites is also of technical, economical, regulatory and land-use concerns.

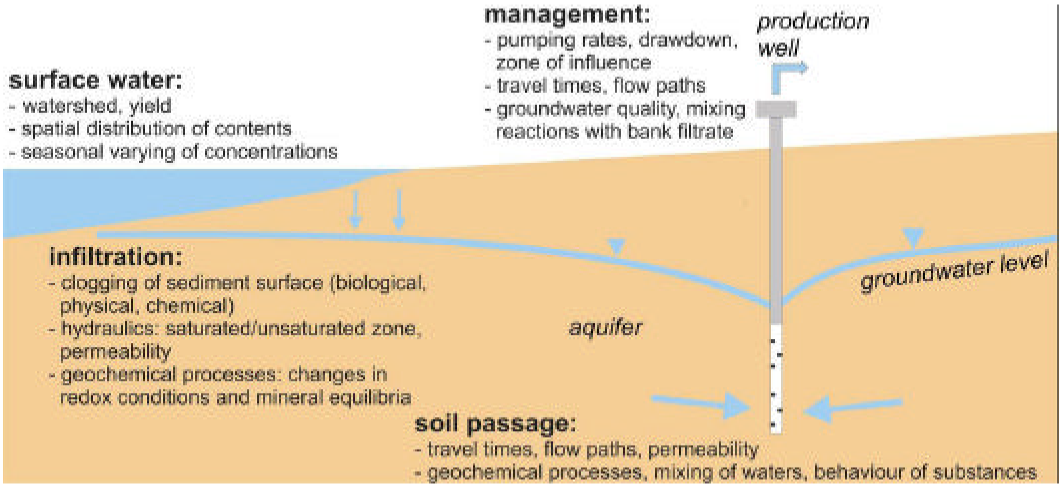


Figure 3.1 Sketch of factors influencing bank filtration (modified from FRITZ 2002)

RBF is recognized to be a cost-effective technology in balancing fluctuations both in temperature and ion concentration (e.g. nitrate, ammonium). In general, the degree of temperature equalization increases with the residence time of bank filtrate during underground passage. Very early it was recognized that RBF is an excellent technology to attenuate and delay shock loads occurred in the surface water due to chemical spills, terrorist attacks or defects in industrial wastewater plants (e.g. KÜHN & MÜLLER 2000). The reduction in concentration during the underground passage is based on varying travel times of the water molecules from the surface water to the abstraction well. Experiences from Germany show that only one to five percent of a sudden short lasting spill can be found in the water of the abstraction well (SCHMIDT et al 2003).

The behaviour of inorganics such as iron, manganese, and various heavy metals is studied by several authors (e.g. SCHMIDT et al 2003). In aerobic aquifer systems ion exchange processes at negatively loaded clay minerals surfaces, amorphous ferric oxides, alumina and organic solid matter is recognized. In anoxic aquifer systems the removal of metal ions is dominated by precipitation reactions with sulphide.

Several studies have shown that RBF is an effective technology to remove and transform pathogens, organic matter, disinfection-by-products and other trace organics (e.g., Cote et al. 2003). Natural organic matter (NOM) is used to describe the complex matrix of dissolved and particulate organic matter occurring in both ground- and surface water. Natural organic matter is known to (i) react with disinfection chemicals to carcinogenic disinfection-by-products (e.g., chloroform) and (ii) cause microbial growth in distribution systems (Pre´vost et al., 1998). Several studies state that the removal and transformation of NOM at RBF through the underground passage is site specific and highly dynamic (e.g. DREWES 2002, HISCOCK & GRISCHEK 2002). But general statements can be made according to: Particular organic matter is early recognized to be removed during the initial phase of infiltration, associated with coagulation and precipitation processes (SONTHEIMER & NISSING 1977). The removal capacity in dissolved organic matter (DOM), investigated in long-term studies by SONTHEIMER 1991, is nearly constant without significantly accumulating organic matter in the subsurface. Recent studies conducted by WEISS et al 2002 state removal proportions up to 50 – 60 % of DOM. Most of the waterborne pathogens use the organic carbon sources for their growth and metabolism (heterotrophic). Another hazard, related to high loads of nutrients from surface runoff by agriculture, is the occurrence of toxic substances such as microcystin from cyanobacteria (blue-green algae). DILLLON 2002 reports the evidence for adsorption and degradation of microcystins in porous media from South Eastern Australia.

Virus removal is considered to be one of the most critical tasks where the purifying capacity of RBF sites can be evaluated. Several studies report about the removal of viruses by inactivation of free viruses and by the absorption to soil grains, followed by inactivation of the absorbed virus (e.g. SCHIJVEN 2002, ZIEGLER 2001). The removal of viruses takes place at the very first meters during underground passage (e.g. SCHIJVEN 2002). The removal rates are very site specific and depend on hydrochemical parameters like temperature, pH, DOC and aquifer properties like grain size distribution, presence of iron, aluminium, or manganese oxides and travel time. SCHIJVEN 2002 studies the fate of viruses and bacteriophages under field conditions in the Netherlands. Under low temperatures (< 15°C) the absorption rates are kinetically limited. Between pH 7 – 8 the surface charge of most viruses and grains is negative causing low absorption rates. At this pH range viruses prefer to attach on sediment which is positively charged, like iron, aluminium, or manganese coatings. The presence of this kind of sediments will increase the removal rates of viruses several orders of magnitude. DOC is found to decrease the removal rates of viruses during underground passage due to competition for the same binding sites (e.g. SCHIJVEN 2002). Depending on the unconformity in grain size distribution it is stated that viruses may travel faster than average advective groundwater flow, due to preferential flow in high permeable sediment passages.

All in all it can be said that water treatment based on RBF can significantly decrease the concentrations of many surface pollutants in the abstracted water. However, a precise prediction of both quantity and quality of the removal capacity is often difficult, since the efficiency depends on many site specific factors as mentioned above. The implementation of RBF as a multi barrier system can greatly improve the capabilities of a whole water supply chain. Nevertheless, it is well known that further research is needed both in developed and developing countries and new industrialised countries to evaluate the water quality treatment during underground passage under diverging conditions (DILLON 2005).

4. Integration of hydrogeological investigations

4.1. Delhi - the study area

The city of Delhi is situated in the central northern part of the Indian subcontinent on the banks of the river Yamuna, approximately 200 km southwest of the Himalayan mountain front. The National Capital Territory of Delhi (NCT) spreads over a total area of 1483 km2, of which more than 60% is now urban (Maria 2004).

4.1.1. Geomorphology

Geomorphologically the study area consists of flat plains interrupted by clusters of sand dunes (197 to 260 masl) and a long continuous chain of rocky ridges known as the Delhi Ridge (Figure 4.1). A topographic depression in the south west margins is locally known as Najafgarh Jheel (Jheel = lake). The Yamuna River, a tribute to the Ganga, flows in a southerly direction through the eastern part of the NCT and is the only perennial river in the area (Central Ground Water Board 2006). The river is dammed in the northern part of the Delhi at Wazirabad barrage, in the central part at Delhi Barrage and in the southern part of the city at Oklah barrage. Between these barrages the River Yamuna is joined by a number of tributaries. These so called drains are generally channelled water bodies used for disposal of urban wastewater and flood control during monsoon season. The most important one is the Najafgarh Drain which has its source in the western state of Haryana and

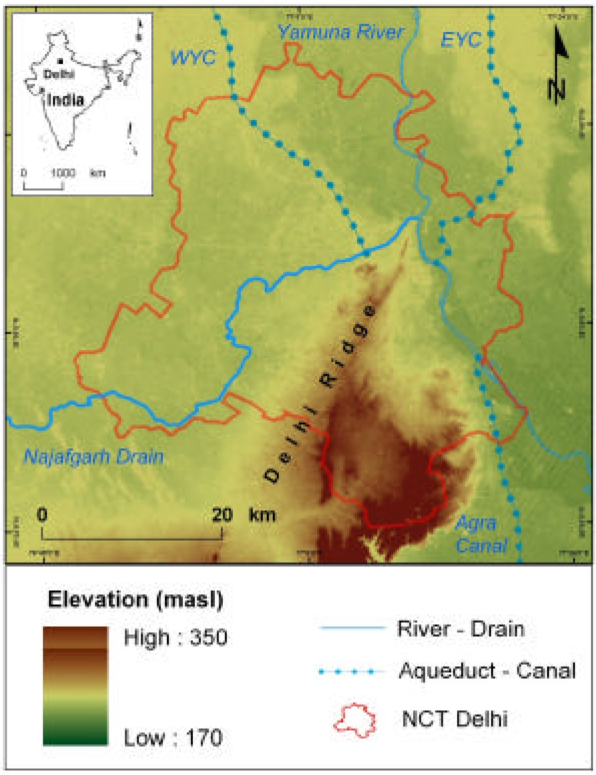
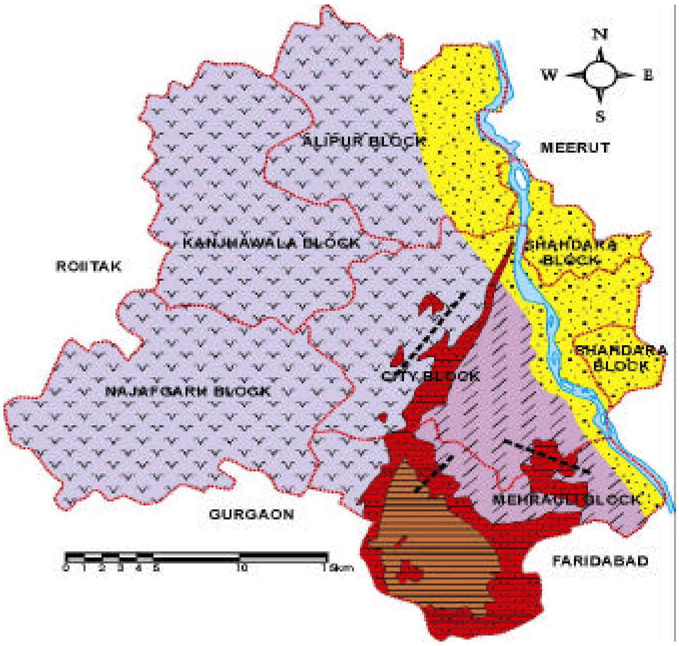


Figure 4.1 Geomorphology of NCT Delhi with the main rivers, canals and drains.

flows into the Yamuna River in the northern part of the city below Wazirabad barrage. At several points, the city of Delhi is connected to a large canal network that had been built by the colonial government at a time where alternative technologies were not available (Sah 2006). Until today, this network is being upgraded in order to improve temporal and spatial distribution of river water throughout the region with the construction of barrages river management and inter basin water transfer (Ministry of Water Resources 2006).

4.1.2. Geology and hydrogeology

The study area is situated within the world's largest terrestrial foreland basin, the Himalayan molasse basin. It has been formed as a result of an uprising of the Himalayan orogen massiv due to the collision of India-Asia continental plates. Due to ongoing convergence, uplift and erosion a continuous sedimentation in a variety of fluvial regimes into the foreland basin took place (Brozovic & Burbank 2000). The only outcrop of the bedrock is represented by the so called Delhi Ridge, a spure of precambian metamorphic rock jutting into the unconsolidated sediments (Kaul & Pandit 2004). On a



	Age-Group		Lithology	Hydrogeological Cond.
Unconsolidated	Quarternary Newer Alluvium		Yamuna sand, silt and clay with gravel	30-40m thick unconfined to semiconfined aquifers
	Tertiary Older Alluvium		Predominantly clay associated with fine graind aeolian deposits	Fairly thick, regional extensive, semi-confined aquifers
			Predominantly clay with silt and kankar	Local, limited thick semi-confined aquifers
Consolidated	Delhi super group (Pre-Cambrian)		Mainly sand with minor silt clay and kankar (chattarpur basin)	Fairly thick regionally extensive aquifers
			Quarzite interclated with mica shist, intuded by pegmatites and quartz veins	weathered, fractured quarzite, highly jointed

Figure 4.2: Geological subdivisions in the NCT
[Map: Based on information of Central Ground Water Board 2006; Table modified from Kumar et al 2006].

local scale, four different units can be distinguished within the study area (Figure 4.2). Physical properties and aquifer characteristics of these units have recently been described by Central Ground Water Board (2006) and Kumar et al (2006) and can be summarized as:

1. Yamuna flood plain deposits: Adjacent to the course of river Yamuna alluvial deposits of sand, silt and clay with gravel reach thickness of about 30 to 40 meters. They build up unconfined to semi-confined aquifers with very large yield potential of 100-280 m^2 / hr.

2. Older alluvium: Extensive tertiary sediments of clay associated with fine grained aeolian deposits form fairly thick aquifers to the eastern and western side of the ridge. They are generally semi-confined with large yield prospects between 30 and 100 m^3 / hr.

3. Chattapur sediments: Isolated alluvial deposits derived from the quartzitic ridge form a fairly thick regionally extensive aquifer. They are consolidated and consist of mainly sand with minor portions of silt, clay and kankar. Yield prospects are low (10-30 m^3 / hr).

4. Delhi ridge: The NNE-SSW trending metamorphic hard rock acts as a groundwater divide between the western and eastern parts of Delhi. Groundwater abstraction potential in the fracturated quartzite is very limited with yield prospects as low as 10-30 m^3 / hr.

4.1.3. Climate

The climate of the Delhi region is of semiarid nature due to marked diurnal differences of the temperature, high saturation deficit and low to moderate rainfall. The climate is markedly periodic and is characterized by dry, gradually increased hot seasons between March and June, a dry and cold winter from October to February and the warm, monsoon period from July to September (Figure 4.2). The average rainfall (1954-2004) is reported to be 721 mm and the mean minimum and maximum temperatures 18.7 and 30.5 °C,

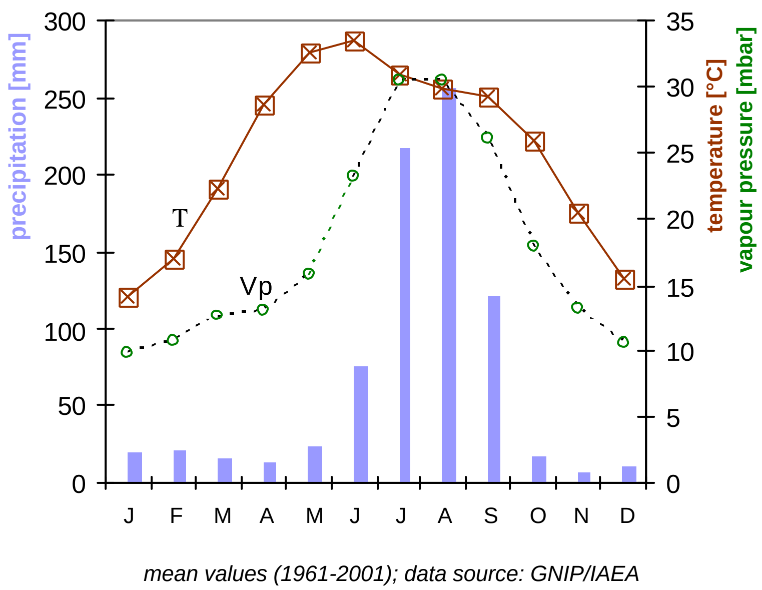


Figure 4.2: Climatic parameters for the city of Delhi. Temperature, precipitation and vapour pressure (mean values from 1961-2001). Data from GNIP database.

respectively (Kumar et al 2006). Regarding these values, one has to consider, that climate parameters are usually being monitored in the central western part of the NCT, but microclimate within the area is highly variable. Isohyetal maps published by Central Ground Water Board (2006) for example show a decrease in mean annual precipitation from more than 700 mm in some zones between the ridge and river Yamuna to less than 400 mm in the west of the NCT. The study area is located in the path of the Indian southwest monsoon movement and receives about 80% of annual rainfall during July to September (Datta & Tyagi 2004).

4.1.4. Water supply

Increasing water demand due to a rapid growth of population (Figure 4.3) along with increasing urbanisation and industrialisation has put the Delhi water supply infrastructure under severe pressure. The government agency responsible for water supply Delhi Jal Board (DJB) reported to have a capacity of supplying of about 650 MGD of which 550 MGD were extracted from surface water and only 100 MGD from groundwater (Daga 2003). Most of the surface water originates from Yamuna River, additional water is supplied through inter basin transfer. The amount of water supplied by the DJB is not sufficient to satisfy the needs of the metropolis. As a consequence of the scarcity, private connections and public standpoint get water only one to four hours a day, with a great uncertainty on the pressure (MARIA 2004).

Another problem causing social discontent is the distribution inequity, partly connected to high losses in the water supply net. With most of the raw water sources being tapped by water treatment plants in the northern part of Delhi (see Figure 4.4) water scarcity scenario is worst in the South (Shiva & Singh 2005). For coping with the unreliability of the public supply people find alternative means legal as well as illegal to acquire their water supply, like boring private wells, purchasing water from private water tankers and purchasing bottled water (Daga 2003). According to DAGA (2003), almost every colony or complex in Delhi has a borewell or a tubewell to complement or to substitute the public supply. There are about 100 000 private run wells legally registered at the Central Ground Water Authority (CGWB), but different sources estimate the actual number of private tubewells between 200

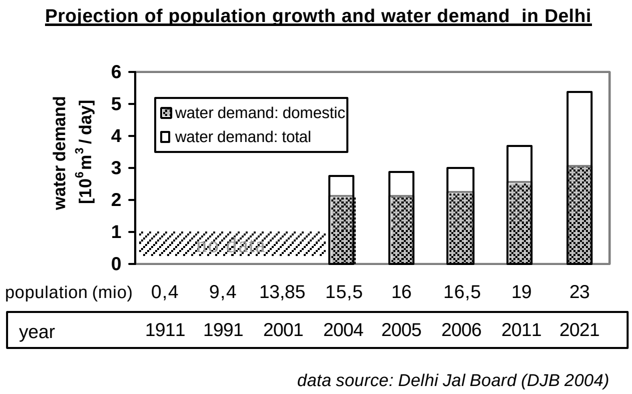


Figure 4.3: Projection of population growth and water demand in Delhi.

000 and 360 000 (Maria 2004). Decreasing water levels are forcing residents to drill deeper and use more powerful pumps with higher energy consumption. Zerah (2006) points out the substantial hidden costs of water supply in Delhi, estimating the collected aggregated cost for coping strategies to represent more than twice the annual expenditures of Delhi public utility.

The use of groundwater for water supply is limited as a consequence of qualitative and quantitative problems. Fluctuation of water level in Delhi has been monitored by CGWB (2006) over several decades. Data published in the Annual Report 2006 indicates a dramatic decline of groundwater level in huge parts of the territory: Between the years 1996 and 2005, descent of more than 2 m was reported from 75 % of the territory and more than 10 m in 16 % of the territory (Figure 4.4). Abstraction is mainly caused by private wells that are present in almost every colony or complex in Delhi, as a result of the shortage in public water supply (Daga 2003). Withdrawal of ground water can by far not be compensated by natural recharge of groundwater. Groundwater recharge rates through rainwater infiltration are reported to be low and most parts of Delhi receive less than 5% recharge. Lateral flow from surrounding areas, canal/river seepage and localized infiltration of highly degraded agricultural and urban surface run-off through stagnant water pools, are the main contributors to the recharge (Datta & Tyagi 2003). In northern Delhi, the Eastern- (EYC) and

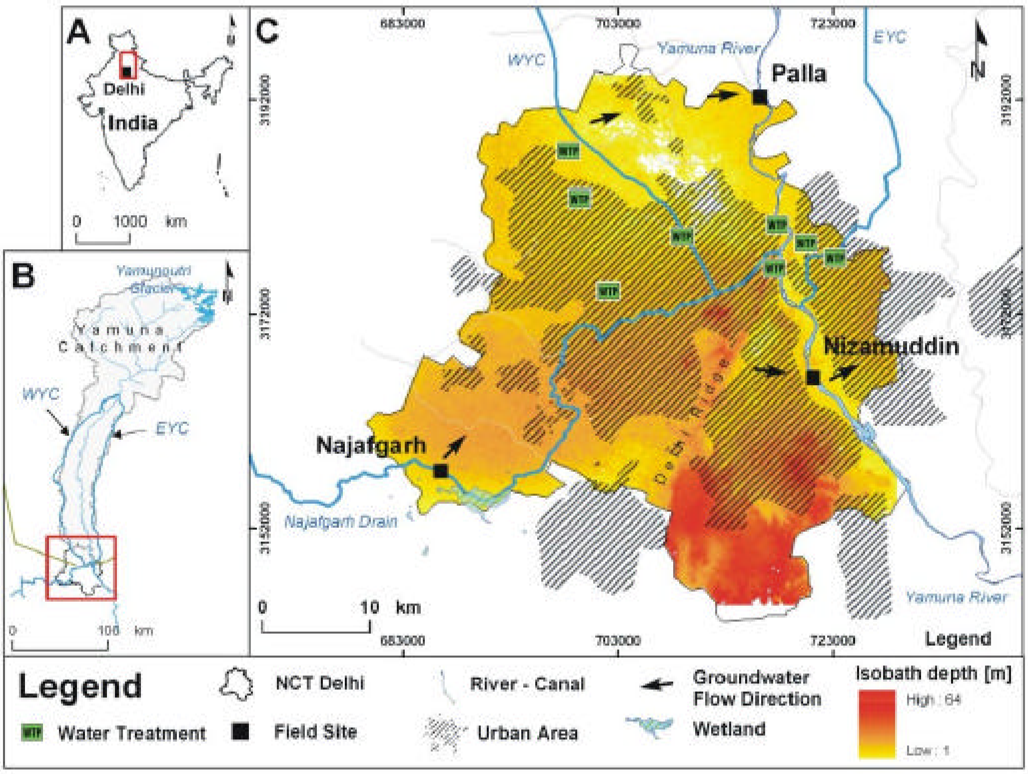


Figure 4.4 A: Overview India. B - Spatial extent of the Yamuna catchment upstream of Delhi and course of the Western- (WYC) and Eastern Yamuna Canal (EYC). C - Location map of the three selected field sites with trends in groundwater flow directions and isobath depths of groundwater.

Western Yamuna Canal (WYC) are representing the margins of the Yamuna watershed.

A widespread problem making the groundwater unfit for its different application are high contents of dissolved salts of chloride and sulphate due to the occurrence of geogenetic saline waters in deeper geological layers. In general, high chloride contents are found in topographic low areas corresponding to discharge zones, while topographic high areas correspond to recharge zones with low chloride concentrations (Datta et al 1996). Along with salinity, fluoride concentration is a major constraint to safe groundwater use for water supply. Fluoride concentration exceeds the WHO norms of 1.5 mg/L in about 30% of the NCT area (Maria 2004).

In addition to the increasing salinization groundwater in Delhi area is getting severely contaminated with nitrate, fluorite, pesticides and heavy metals from anthropogenic toxic waste sources. Unplanned disposal of anthropogenic wastes resulted in excessive accumulation of pollutants on land, into river, unlined drains and landfills. Subsequent leaching of these pollutants causes severe degradation of the groundwater (Datta & Tyagi 2001). Amongst these contaminants nitrate contamination is assessed to be the most alarming problem in Delhi´s groundwater and may mainly be caused by agricultural input of fertilizers and by landfill leachate.

4.2. Upgrade of field sites

The investigation of RBF processes in the mega city of Delhi is based on a detailed study of interaction processes between surface water and groundwater at three different field sites (Palla, Najafgarh, Nizamuddin). The sites have been selected for the installation of RBF systems during the preliminary study. The sites are representing a broad variety of hydrochemical and hydraulic conditions in the surface water and the adjacent aquifer and are described in the following section in detail.

At each of the field sites several piezometers (ground water observation wells) have been drilled to have a close, detailed look to the geological and hydrogeological settings. Drilling is important for both getting a rough idea of aquifer composition and local geological strata as well as for groundwater monitoring.

The number and design of piezometers was based on the following concept: At least three piezometers in a triangular shape are essential for determination of groundwater surface slope and subsequent calculation of flow direction and hydraulic gradient. These piezometers may be constructed in relatively shallow groundwater, which is expected to be most influenced by interaction with surface water. For being able to analyze the interaction processes between shallow and deeper groundwater, at least one piezometer should tap a deeper horizon of aquifer and another piezometer should be installed in an intermediate level. In areas of high risk of salinisation, where saline water is covered by a limited horizon of sweet ground water, the filter screen of the deep piezometer should tap saline water whereas the intermediate should be installed in the saline water ground water interface. In this case multi level observation points can indicate fluctuation of saline water – sweet water interface and mixing of end members (Figure 4.5).

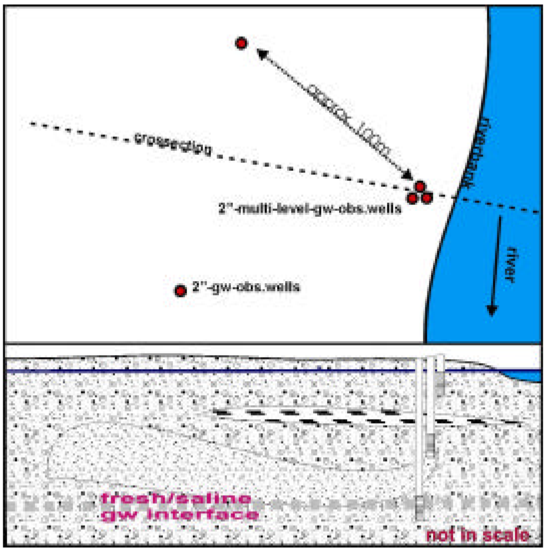


Figure 4.5 General piezometer setup.

4.2.1. Drillings and lithological logs

Drilling campaigns were carried out at the three selected sites (Palla, Najafgarh and Nizamuddin) between November 2006 and January 2007 in order to install the required observation wells.

Due to technical and logistical problems the spatial distribution of the piezometers at the field sites may differ from the proposed concept described in section 4.2.

Lithological logs were made on site with the available drilling samples to provide information about sedimentological aspects such as lithology, stratigraphy, grain size distribution and thickness and also hydraulic properties such as porosity and hydraulic conductivity. A summary of the field parameters gives Table 4.1, where the coefficient of hydraulic conductivity was estimated according to an empirical table.

Table 4.1 Site, stratigraphy, lithology and coefficient of hydraulic conductivity.

No.	Site	Stratigraphic Unit	Lithology Description	depth below ground level [m]	k_f [m/s]
1	Palla	Younger Alluvium Older Alluvium	medium to coarse sand with kankar (gravel), mica fine to medium sand	0 - ca. 20 ca.20 - 54	5.0e-4 - 8.0e-4 1.0e-4 - 1.0e-5
2	Najafgarh	Older Alluvium	silt to fine sand, calcitic matrix	0 - 34	1.0e-6 - 1.0e-5
3	Nizamuddin	Younger Alluvium Older Alluvium Hardrock (Quartzitic Ridge)	medium to coarse sand with kankar (gravel), mica fine to medium sand quartzite, schist	0 – ca.10 ca.10 - 30 > 30	5.0e-4 - 8.0e-4 1.0e-4 - 1.0e-5 Aquiclude

4.3. Site specifications

After evaluation of available information and interpretation of own experience during drilling and water sampling campaigns, a detailed prescription of the site specific conditions can be given according to:

4.3.1. Palla

This site is located in the northern part of Delhi, on the flood plain of the western bank of the river Yamuna upstream of the urbanised parts of Delhi. The well field stretches on the western bank of river Yamuna from the northern outskirts of urban Delhi until the Haryana border over a total length of about ten kilometres occupying an area of about 18 km2. The floodplain is bordered on both sides by a dike that has been built in a distance of 0.5 – 2 km from the actual course of River Yamuna to protect the populated hinterland from flood events. According to the statements of Central Ground Water Board officials a major flood event, setting the entire floodplain area under water has not occurred for at least 5 to 10 years. Anyhow, the floodplains are largely recharged during monsoon season. All wells are constructed on ca. 3 m pylons to obtain pumping also during flood events. Contamination of the river water and adjacent groundwater is low, so that Delhi Jal Board is able to run a well field to abstract groundwater for drinking water production. About 15% of the public water supply is contributed by the well field.

The geology of the floodplain and surroundings is dominated by sandy fluviatile deposits which built up the younger alluvium, covering the entire area with a thickness of tens of meters. These sediments have been deposited upon a series of several hundreds of meters of older alluvium, which is predominately composed of fine sand, silt and clay.

Morphologically the well field lies as a relatively plain terrain between the dike in the west and the slope of the riverbed in the east. The land is being used intensively by the farmers of the surrounding villages for cultivation of different kind of crops like turnip, rice and wheat. Within one year the course of the river seems to be relatively stable, meandering only within the slopes of the riverbed, with shifting sand banks and high fluctuations of water level throughout the seasons. Anyhow, oxbow lake structures within the floodplain and comparison of satellite images and maps from different years show that locally the riverbed has shifted several hundred meters throughout the last decades (Figure 4.7).

Ground water level is reported to be found at about 4-6 metres below ground level. Saline and brackish ground waters that occur in deeper wells are covered by a horizon of some tens of meters of sweet water in the floodplain area. Salinisation is a major problem all in the southern part of floodplain area. Chemical analysis of water from two exploratory wells in the floodplain are reported to show all parameters to be within the stipulated drinking water standards but the presence of faecal coliforms makes adequate disinfection necessary (Economic Survey of Delhi 2001 / 2002, DWSSP 2004).

The piezometers have been constructed right in between the river and a tube well of Delhi Jal Board (here PA-TW). Seven piezometers have been drilled at the Palla field site. Due to a collapsed borehole at the multilevel position, the deep borehole (PA-PZ-3) was shifted about 7 m to the NW (parallel to the river). The piezometer PA-PZ-7 was constructed to detect the influence of

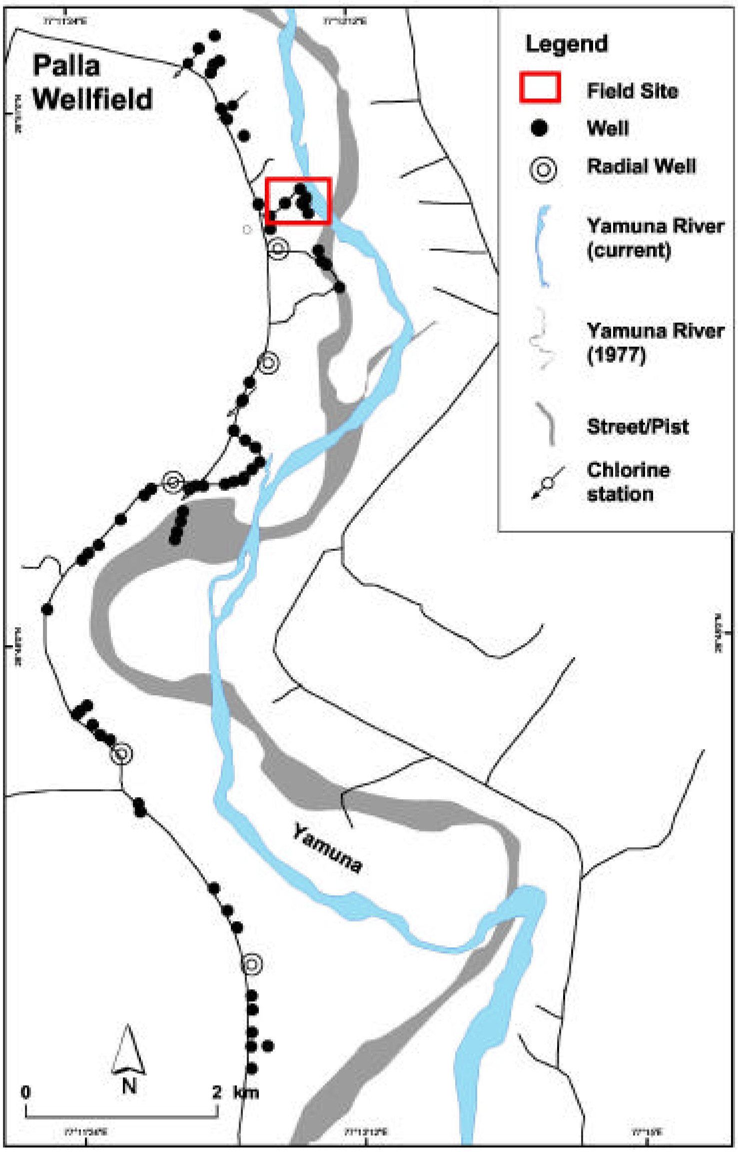


Figure 4.7 Palla well field with the field site in the north.

groundwater from the hinterland. The exact piezometer setup is shown in Figure 4.8. The assembly and the lithological log for each observation well and the abstraction well is shown in appendix, figure a1-a8. At this site the static water level can be found 4-5 m below surface. In this terrain the upper sediments are found to be medium to coarse sand with kankar (carbonate concretions) in gravel size. The high mica content is characteristic for sediments of the younger alluvium unit. The older alluvium was encountered between 18 – 22 m below ground level and is to be found fine to medium sand. The mica content decreased and silt/clay lenses can be found. This fining up in grain size is expressed by a relatively low coefficient of hydraulic conductivity around $1x10^{-4}$ – $1x10^{-5}$.

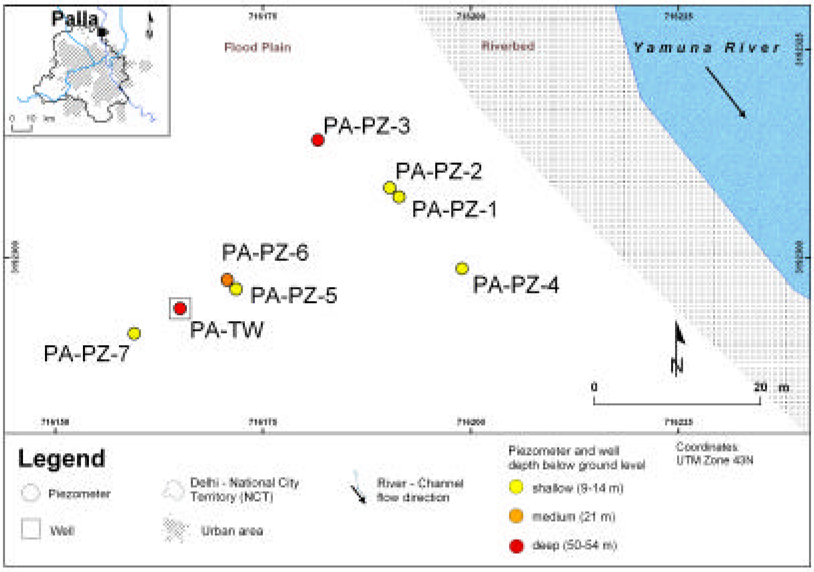


Figure 4.8 Piezometer setup in Palla.

4.3.2. Najafgarh

This site is situated in the rural southwestern part of the NCT at the Najafgarh Drain approximately 10 km south-western of Najafgarh Village. The Drain flows from the NCT border in the west to the east before it bends to the north and then merges with Yamuna River. The drain is used as a sewage canal as it flows to the urbanised parts of Delhi. At the field site contamination level is relatively low. The main problem in this area is that groundwater is highly affected by salinisation. At this segment, the drain is being divided into two parallel channels. The point of divide is situated some four kilometres upstream where the drain is dammed on a weir before it enters Delhi territory from Haryana (Figure 4.9).

Morphologically, the region presents a wide open plain, separated from the course of the river Yamuna by the Delhi Ridge to the east. The Delhi Ridge consists mainly of quartzites with intercalations of schist phyllite and belongs to the proterozoic Delhi Super Group (Kaul & Pandit 2004). The landscape is characterized by a wide open plain surface, which is used for agriculture by the farmers of the small villages spread around the area. Central Ground Water Board reports that borehole data shows that geology of the whole area is dominated by alternate fluvial and aeolian bands. Sediments are described as mostly silt with medium to fine sand and clay (Shekhar 2006). Regional maps published by CGWB [http://www.rainwaterharvesting.org/index_files/water_level_fluct.htm] and by Kumar et al (2006) show that groundwater level in the area has to be expected at about 5 m below ground level at an absolute level of about 205 mNN with a flow direction in a north-eastern direction (Figure 4.10).

Before 1886, when the Najafgarh Drain has been excavated by the British to reclaim fertile land, there has been only a series of ditches. From the so called Najafgarh Jheel (Najafgarh Lake) which has once spread over an area of estimated 88 sq miles or 227 km2 (The Times Of India, from 11.09.2006) today only a small lake of 7.2 km2 remains. It is situated approximately 4 km downstream of the field site location at the Delhi- Haryana border in the southernmost section of the Najafgarh Drain, at the inflow of the channel originating from Gurgaon water treatment plant (Figure 4.10A).

The field site has been placed on the dike that had been built on the northern side of the drain to protect the hinterland from flooding. The site can be reached over the small road in top of the dike and lies about 150 meters east from the bridge over the Najafgarh Drain where the major road is connecting the villages of Ujwah / Jhulijhuli and Raota.

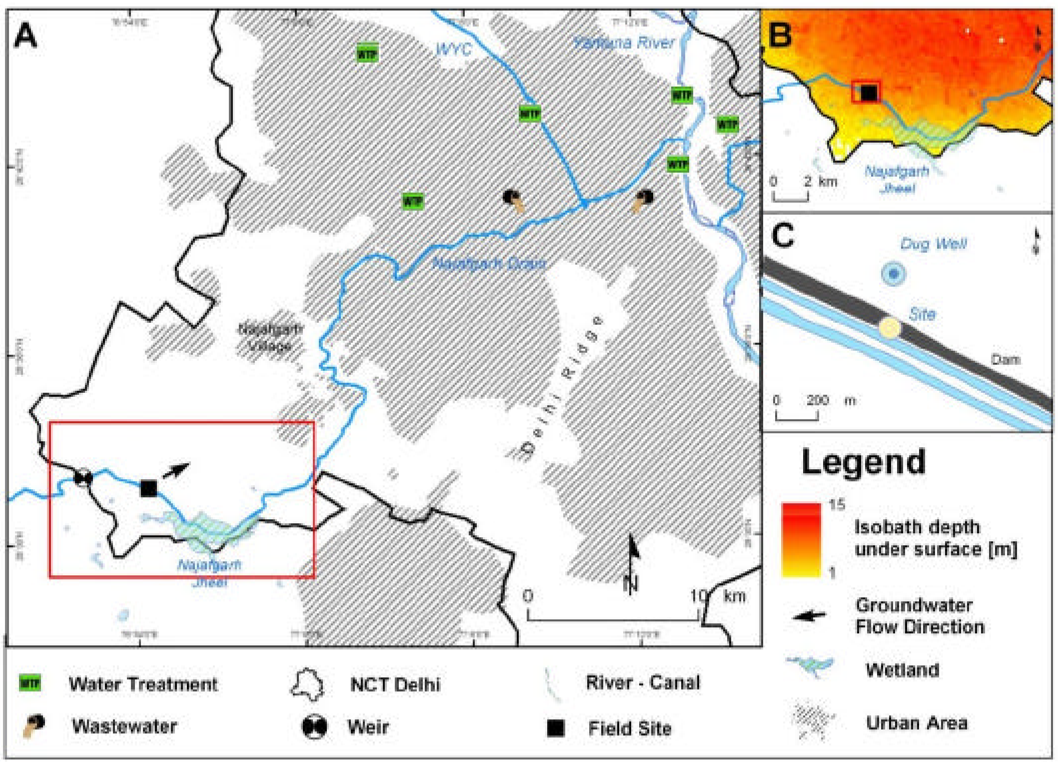


Figure 4.9 A –Najafgarh Drain overview. B – Isobath map of the southwestern part of Delhi. C - Najafgarh Drain field site.

Regarding ground water quality, salinization is most urgent problem in the area, with EC values measured as high as 37,820 µS/cm (Bhawna &

Ramanathan, n.d.). Maps published by Shekhar (2006) show that inside the Najafgarh depression freshwater of more than 10 m of thickness is only found in small freshwater pockets stretching along the drain and its tributary.

In Najafgarh 5 piezometers have been drilled and the exact piezometer setup is very close to the proposed concept (Figure 4.10). The assembly and lithology for each piezometer is shown in appendix, figure a9-a13. At this site the static water level can be found 2-3 m below surface. In this terrain silt to fine and sporadically medium size sands were found. These sediments were interpreted as alternating fluvial sequences distributed with a high spatial variance in thickness. The coefficient of hydraulic conductivity (kf) ranges between $5x10^{-4}$ – $8x10^{-4}$ for the younger alluvium unit and between $1x10^{-4}$ – $1x10^{-5}$ for the older alluvium unit.

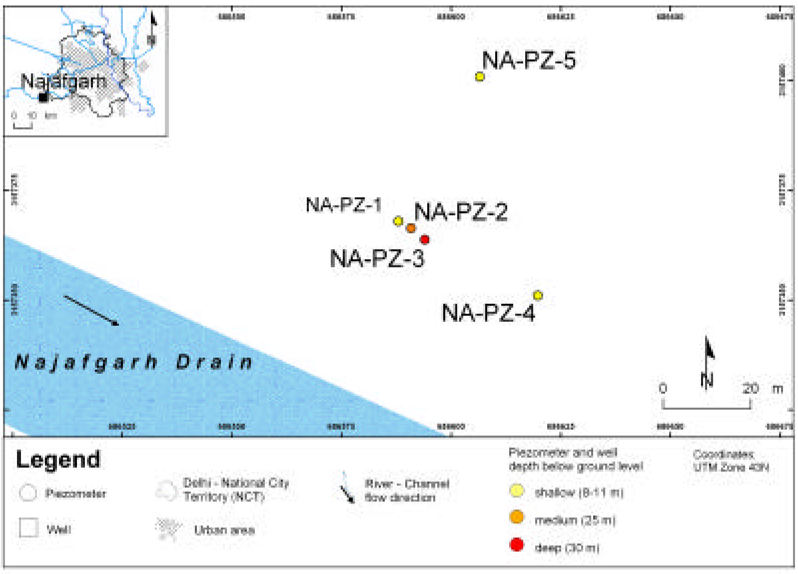


Figure 4.10 Piezometer setup in Najafgarh.

4.3.3. Nizamuddin Brigde

The location for the third field site is situated in the urban central part of the city of Delhi, on the eastern bank of River Yamuna, about 100 meters upstream (i.e. north) of Nizamuddin Bridge. Piezometers have been built along the river, on a sandy bank of about 50 to 200 meters of width (Figure 4.11). This bank presented itself as a muddy field at the end of monsoon season in late August of 2006. Some 30 meters upstream of the field site, there was a small lake of about 100 meters of diameter within the bank, which was connected to the river through a natural channel. By the end of October of 2006 anyway the terrain had dried up and was ploughed up by local farmers for agricultural use. The only thing left from the lake was a small isolated waterhole (about 50 m of diameter) in the centre of a muddy depression. Most probably the bank has been at least partly flooded during July/August of 2006 thus it might be covered under water again during proximate monsoonal events.

Landwards, the bank is separated by a slope of only a few meters height from a superior flood plain terrace in the back land, which is another 2 km wide. As this terrace has not been flooded for many years, it is permanently being used for agriculture and market-gardens. Recently some outlying terrains have been dammed up for urban development measures. Within this area, Delhi Jal Board is operating some large Ranney Wells (radial collector wells with multiple horizontal screen laterals) and recently a number of tubewells have been constructed. The field site has been placed in a straight line right in

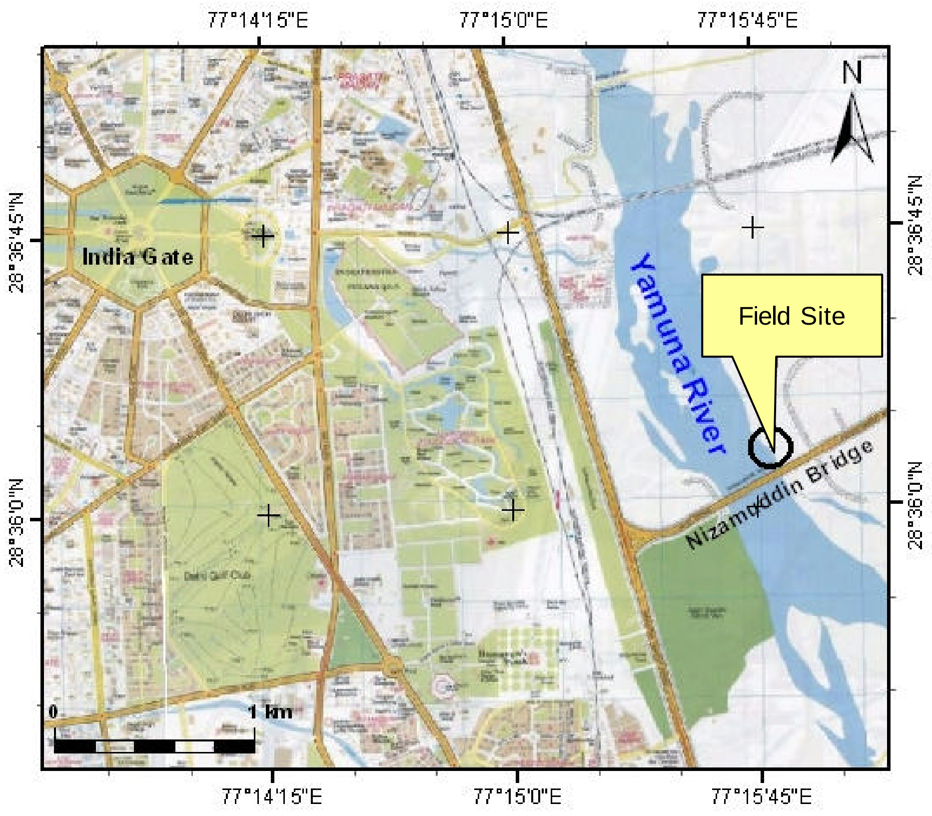


Figure 4.11 Nizamuddin bridge field site.

between two of the Ranney wells and the river. The first Ranney well lies in a distance of about 1100 m from the river the second one is only some 400 m away from the river is currently not being operated due to high ammonia contents in groundwater, but kept as a reserve for potential bottlenecks in water production. According to the maps published by Kumar (2006), upper sediments within the area are composed of Yamuna sand, silt and clay with gravel. Groundwater level should be found only a few meters below surface and flow is expected to be directed towards the east. Salinisation is not known to be a major threat on groundwater quality this area, but problems with ammonia show that infiltration of highly contaminated river water may have a clear negative impact. Within this segment in Central Delhi, River Yamuna is highly contaminated by discharge of sewage and industrial wastewaters. Quite alarming is comtamination with pathogens and organic pollutants in wastewater (Kumar 2002, Walia & Mehra 1998, Agarwal et al 2006) but also concentrations of heavy metal load in river sediment (Singh 2001).

In Nizamuddin 5 piezometers have been drilled. Due to a problem with a farmer the piezometer PA-PZ-5 is only about 5 m away from the multilevel piezometers (Figure 4.12). The assembly and the lithology for each piezometer are shown in appendix, figure a14-a18. At this site the static water level can be found 1-2 m below surface. In this terrain the unconsolidated sediments were divided in two units analogous to the Palla field site. At a depth of 30 m below ground level the quartzitic hardrock was encountered. Due to low permeability of the hardrock this unit is considered as a aquiclude.

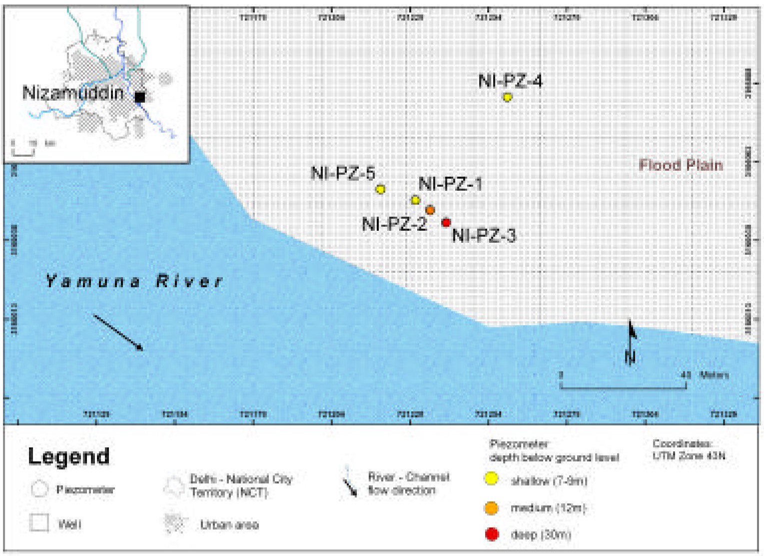


Figure 4.12 Piezometer setup at Nizamuddin bridge.

4.4. Sampling campaigns

The objective of a good sampling campaign should be the collection of a representative sample of the current groundwater over a specified volume of the aquifer. To meet this objective, the sampling equipment, the sampling method, the piezometer construction and sample-handling procedures should not alternate the chemistry of the water sample.

Since December 2006 sampling campaigns were carried out at the selected field sites. The samples were taken according to the DVWK 1992 guidelines. The minimum necessary equipment is (Figure 4.13):

- Steel tape with weight (used for measuring total depth of well)
- Depth-to-water measuring device (light plummet)
- Sampling pump (submersible pump, 12 V DC)
- Power supply (12 V DC accumulator, wire)
- Flow measurement equipment (water meter, stop watch)
- Flow-through cell (with measuring devices described in Appendix,Table 1)
- Decontamination supplies (distilled water, paper tissues)
- Sample bottles (20 ml polypropylene, water proof labels)
- Filtration equipment (cellulose filter, hand vacuum pump)
- Tool boxes (steel boxes with tools)

Figure 4.13 Measuring setup at a piezometer (flow-through cell, accumulator, light plummet, water meter)

4.4.1. Water level and total well depth measurements

The field measurements of total well depth and depth to water were done from a permanently-marked reference point. This reference point is the top of the iron case of the piezometer (top of piezometer).

The total depth of each piezometer was measured with a weight attached steel tape and documented in Appendix, Figures a1-a19. Additionally, the distance between top of the piezometer and ground surface was measured. The depth to water was measured with a light plummet prior to any other activities at the piezometer.

4.4.2. Static water volume

From the information obtained for casing diameter (here 4“ or 10.16 cm), total well depth and depth-to-water measurements, the volume of water in the well was calculated. This value is a criterion that was used to determine the volume of water to be purged from the well before the sample is collected.

The static water volume was calculated using the following formula:

$$V = \frac{d^2 p}{40} \cdot h \qquad \text{(eq.1.0)}$$

where:

V = Volume [L]
d = casing diameter [cm]
h = height of static water [m]

4.4.3. Piezometer purging volumes

In most cases, the groundwater in the piezometer casing can be of a different chemical composition than that in the aquifer. Solutes may be adsorbed or desorbed from the casing material, oxidation may occur, and biological activity is possible. Therefore, the static water within the well must be purged so that water is representative for the aquifer.

The removal of at least 3 piezometer volumes is suggested by many authors and guidelines (e.g. DVWK 1992) and was applied in this study. The amount of water to be removed was calculated according to eq. 1.0, multiplied by 3 and measured by a flow meter (Figure 4.14).

The number of purging volumes to be removed is based on the stabilization of hydrochemical/-physical parameters such as temperature (T), pH, oxidation-reduction potential (ORP), electrical conductivity (EC), dissolved oxygen (DO) and turbidity. These measurements were taken and recorded in certain time steps until the parameters were stable. The complete field protocol for sampling is shown in Appendix, Table a19.

4.4.4. Sampling procedure

In-situ parameters (pH, T, ORP, EC, DO) were measured with Eutech devices (Appendix, Table a1) in a flow-through cell. The flow-through cell consists of a transparent chamber through which water moves in a constant flow from the bottom to the top. The electrodes measure groundwater that has not yet been in contact with the atmosphere (Figure 4.14).

After the in-situ parameters were considered as stable the samples were taken and stored in 20 ml polypropylene (PP) bottles with watertight caps. All samples for ion determination were filtered on site with 0.2 mm acetate cellulose filters. The sample for cation measurements was acidified to pH 2 with ultra pure HNO_3 and one bottle of each sample (not acidified) was kept for anion determination. Additionally, one 20 ml PP bottle for each piezometer was taken for stable isotope (d^2H and $d^{18}O$) measurement.

Alcalinity was determined by HCl titration in field for the determination of the HCO_3^- species using a Merck Acidity test. Nitrite, ammonium and sulphide content were determined on site by colometric tests (Appendix, Table a2).

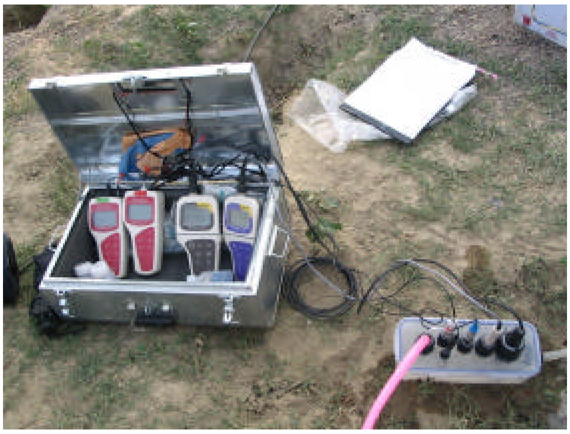


Figure 4.14 Measuring in-situ paramters on site (flow-through cell, measuring devices in steel box).

4.5. Hydaulics – aquifer tests

Pumping tests were conducted at the Palla field site and the aquifer test data were analyzed by conventional analytic methods using the software AQTESOLV 3.5 for Windows (DUFFIELD 2003). These methods are used to obtain estimates of hydraulic properties such as horizontal and vertical conductivities, specific storage, and specific yield. A representative pumping-time schedule of the Palla well is shown in Figure 4.15. The well is abstracting water between 6-9h per day with an estimated discharge of 2000 L / min. The drawdown in the well could not be measured and is estimated to be 15 m. The recorded hydraulic heads from an observation well (PA-PZ-6), which is situated 7 m from the well, are showing maximum drawdown depth of 4.5 m. The well is partially penetrating with total depth of 54 m below ground level and exact aquifer thickness is unknown. The water table is about 5 m below the ground surface and geology is described in detail in section 3.0. In the observation well, (PA-PZ-6) equipped with pressure transducers and temperature logger, the time of monitoring of hydraulic heads was event based. The logger unit is situated 5 m below the water table. The accuracy of the pressure transducers is listed in appendix table a3. Groundwater recharge and barometric pressure changes were neglected in the analysis because of the short duration of the pumping test.

The best developed drawdown curve and the following recovery period (from noon to 5 pm) was taken for the analysis. The course of the temperature reveals first insight in the flow regime. The drastic increase of ca. 2°C at the beginning of pumping reflects the spontaneous vertical movement of shallow warm groundwater due to the abstraction. Later the temperature is decreasing due to flow of colder groundwater from a lower section.

For an unconfined aquifer Neuman 1974 solution for the drawdown and

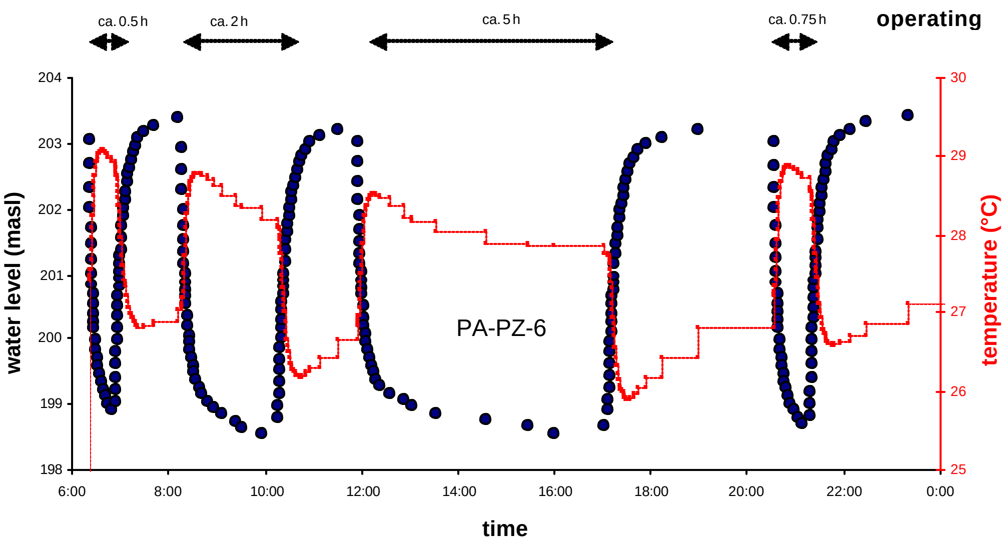


Figure 4.15 Hydraulic heads and temperature log for the Palla well. Recorded at observation well (PA-PZ-6).

recovery period was applied. The analytic methods account for delayed gravity response and partial penetration of the well. The method has assumptions, such as infinite areal extension of the aquifer, homogeneity, unsteady flow, uniform thickness and isotropy. For each test, an aquifer thickness equal to the depth of the pumping well (54 mbgl) was assumed.

The observed drawdown (m) - time (sec) data is plotted in log - log scale in Figure 4.16. The reactions in hydraulic heads can be subdivided in three phases. I) The first phase reflects the initial behaviour of the aquifer as a confined aquifer and the specific storage (S) is obtained by this phase. In this initial stage the Theis method can be applied to the early time of the drawdown curve. The specific storage (S) computed from this segment of the curve, however, cannot be used to predict long-term drawdowns. II) The second phase represents the dewatering of the depression cone and the inflow of the near river. The effect of the dewatering on the drawdown is comparable to that of leakage. The increase of the drawdown slows down with time and thus deviates from the Theis curve. III) The third phase is not good developed but reflects the delayed drawdown and the later unconfined behaviour of the aquifer. This late-time segment of the curve again conform closely to the Theis type curve, thus enabling the late-time drawdown data to be analyzed by the Theis equation and yielding the transmissivity and the specific yield Sy, of the aquifer (Figure 4.17).

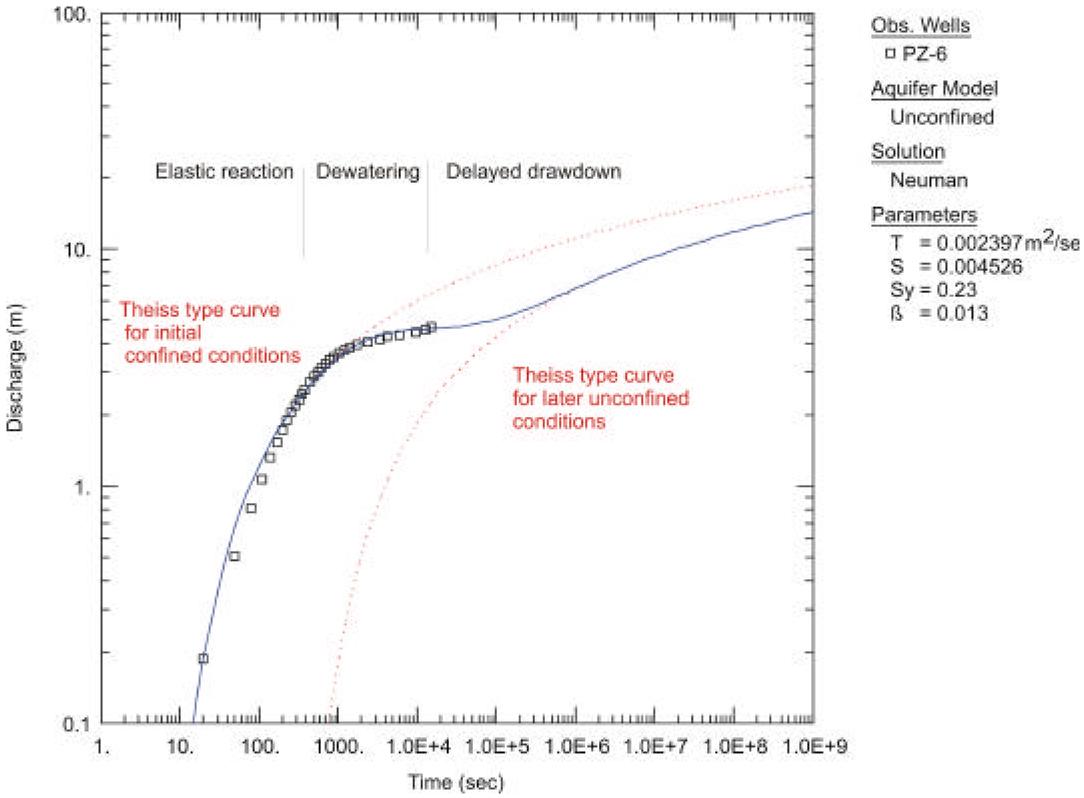


Figure 4.16 Neuman solution for the drawdown period at PA-PZ-6.

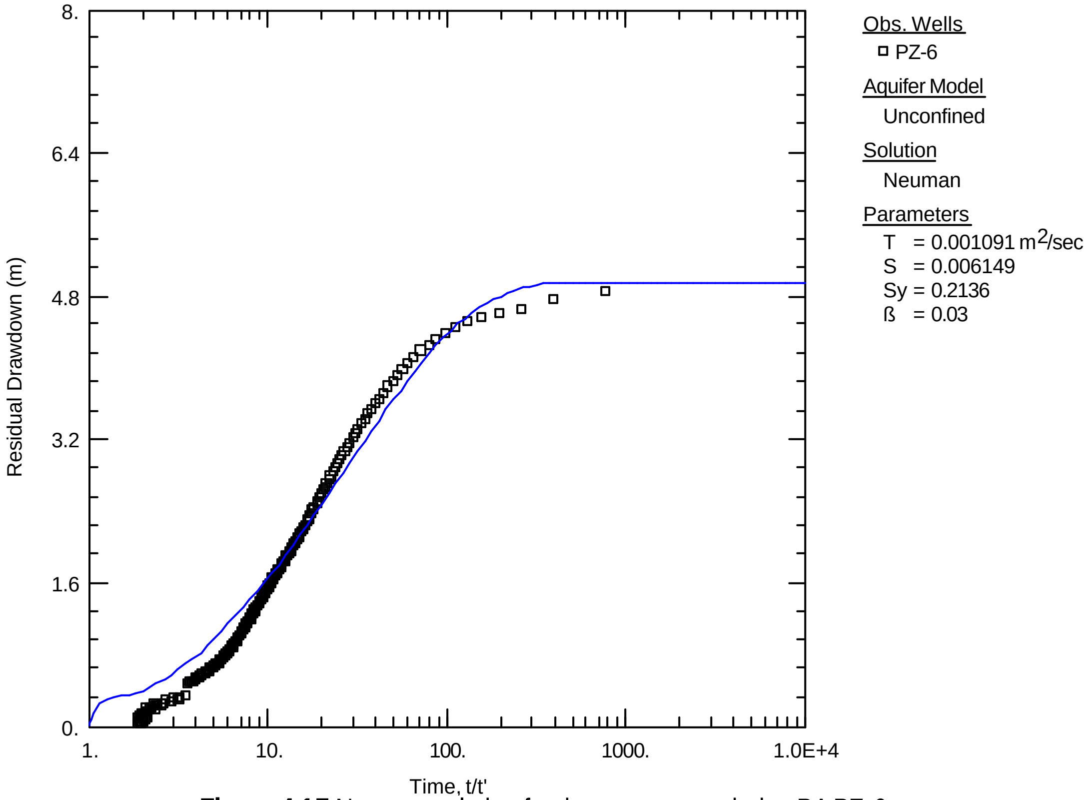


Figure 4.17 Neuman solution for the recovery period at PA-PZ-6.

To evaluate the gained aquifer parameters of the drawdown curve matches, also the following recovery period was analysed. The observed residual drawdown (m) - time (sec) data was plotted in simple log scale in figure 4.17.

A reasonable type curve match for the drawdown and for the recovery period was achieved. Values for T, kv/kh and Sy are quite similar (table 3.2). The specific yield Sy is in unconfined equal to the effective porosity, but values for Sy are not easy to obtain. Particularly Sy is subject to error (Neuman 1979). Typical ranges for a fine – medium sand are for Sy = 0.33-0.32 (Morris & Johnson 1967). Thus the pumping test may underestimate the effective porosity of the aquifer and must be evaluated. By dividing the yielded transmissivity T through the assumed aquifer thickness (54 m) it is possible to calculate the hydraulic conductivity kf. These values can be compared to the kf values obtained by field estimations during the drilling campaigns (see Table 4.2).

It is recommended to run the pumping wells only in the second phase as described before. To obtain a maximum proportion of bankfiltrate it is recommended to run wells only few hours rather than full days.

Table 4.2 Pumping test summary

Solution	T [m^2/s]	S_y	k_f [m/s]	kv/kh
Neumann solution - drawdown	0.001685	0.23	3.12×10^{-5}	0.7
Neuman solution – recovery	0.001091	0.21	2.02×10^{-5}	1

It is important to recognize that the data obtained by the pumping tests are not ideal because of the presence of other wells in the vicinity of the abstraction well. However, it is acknowledged that the drawdown data is not ideal and therefore, the results from PA-PZ-6 should be viewed with caution.

4.6. Temperature profiles

Groundwater temperature is a parameter that is relatively easy to determine and can provide valuable information for multiple purposes. It has been used to identify natural as well as anthropogenic influences on the temperature field of geological units but also to achieve information about the design and functionality of wells (Ländergemeinschaft Wasser - LAWA (1987). Because of it´s tracer like features heat carried by groundwater could successfully be utilized to determine recharge and discharge rates, flow patterns and aquifer parameters in different studies. Recently, applications have significantly expanded to a variety of hydrogeological settings using new techniques like coupled ground water and heat-flow models (Anderson 2005).

First step for working with ground water temperature (geo-thermometry) is the monitoring of temperature variation in time and space. For this purpose a temperature logging is being performed monthly, recording the temperature gradient in the deepest piezometer of each of the three field sites (Figure 4.18).

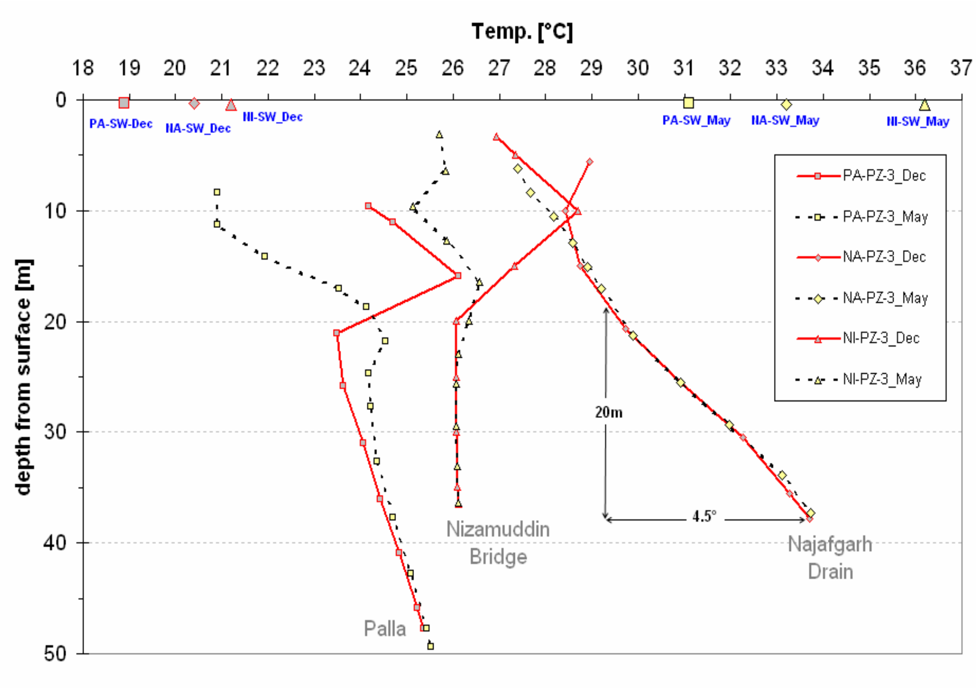


Figure 4.18 Temperature logs from the months of December 2006 and May 2007, showing actual temperature gradient in the deepest piezometers of each field site. Surface water temperatures of adjacent water bodies and temperature gradient at Najafgarh Drain are also indicated.

For a proper interpretation of the temperature-logs, the data of an annual cycle will be necessary, but some details can already be interpreted from the logs shown in Figure 4.19:

- The surface near temperature field around all piezometers is changing through the year, due to the seasonal changes in surface temperature and / or the influence infiltrating surface water.
- Compared to the surface water temperature of the each month and air temperature (see Figure 4.19), surface near groundwater shows a marked delay, corresponding to site specific heat transport and infiltration flow conditions.
- At Najafgarh drain area, the influence from surface seems to be limited to the uppermost 10-15 meters, whereas in Palla well field seasonal changes can be detected up to 35 meters below ground level.
- The deeper part of each curve appears unchanged from May 2006 to December 2007, indicating a stable local temperature gradient, beyond the influence of the seasons. Within this range, temperature trends to increase with depth, at Najafgarh Drain and Palla field site. Especially at Najafgarh drain the gradients the temperature increase of about 4.5° in only 20m is extremely high compared to the normal geothermal gradient of the earth's continental crust of around 3° per 100m.

- An almost stable temperature between 20 and 38 m bgl at Nizamuddin ridge can be interpreted as evidence for horizontal water flow (convection).

5. Perspectives

A time schedule for the next 12 month is given in Figure 5.1. A Major task for the following 6-month period (May 2007 – December 2007) is ascertaining data for implementation into models. Therefore the following field work and laboratory activities will be continued in cooperation of IIT and FUB:

- Monthly sampling of groundwater and adjacent surface water on all field sites.
- Chemical analysis of water samples in IIT and FUB laboratorys, including inorganics (major ions and tracers), stable isotopes (d^{18}O, d ^{2}H), bacteria (total colif., faecal colif.) and additional parameters (viruses, pesticides, pharmaceutical residues)
- Temperature logging and monitoring of water level fluctuations by the use of P-T-data loggers and monthly checking.
- Additional field studies to get further information of site specific parameters (open end hydraulic tests, pump tests, discharge behaviour of river / drain, etc.).

Simultaneously, flow and transport models will be developed to simulate hydraulic conditions. By the operation of these models specific parameters like travel times can be calculated in order to understand the influence of pumping schedules on groundwater flow.

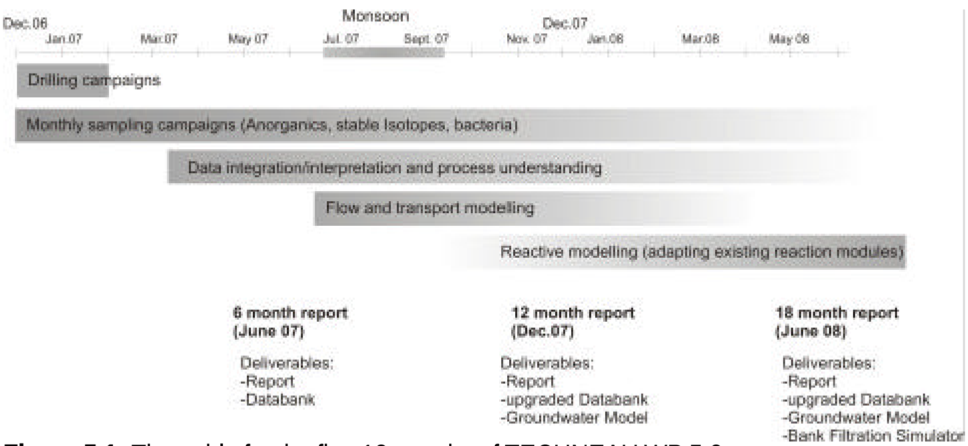


Figure 5.1: Timetable for the first 18 months of TECHNEAU WP 5.2

In the next step the quantification of the interaction between physical (flow, transport) and geochemical (reactive) processes will be investigated. For the calibration of these models applicable tracer substances have to be found. Possible trace substances are listed in Table 5.1. One key parameter for these tasks with good tracer attributes and a clear seasonal signal in the surface water over Delhi are expected to be the stable isotopes. For a better understanding for further modelling the knowledge about the behaviour of the potential tracer substance in the surface water and the groundwater throughout of a full annual will be present from groundwater sampling and analysis. Integration of the data and the further improvement of the system understanding is, of course, a long term task throughout the entire period of the project.

Table 5.1: Tracer substances and their application.

Tracer:	Origin:	Useful for the interpretation of:	Difficulties:
stable Isotopes	surface water with seasonal variations	flow velocities, proportion of bankfiltrate, origin	water rock interactions
temperature	surface water with seasonal variations	flow velocities	retardation
Cl-	surface water with seasonal variations	flow velocities, proportion of bankfiltrate	only if influence of deep saline groundwater and anthropogenic impacts can be excluded
Cl-, Na+, B	saline deep aquifer	proportion of deep saline groundwater	determination of end-member

The NASRI Bank filtration simulator will be utilized to simulate Bank Filtration as observed on the investigated field sites. Monitoring parameters (tracers and hydraulics) will serve to calibrate the simulation and verify the feasibility of the software.

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Appendix

Table a1 Measuring devices, parameters, accuracy and measuring range.

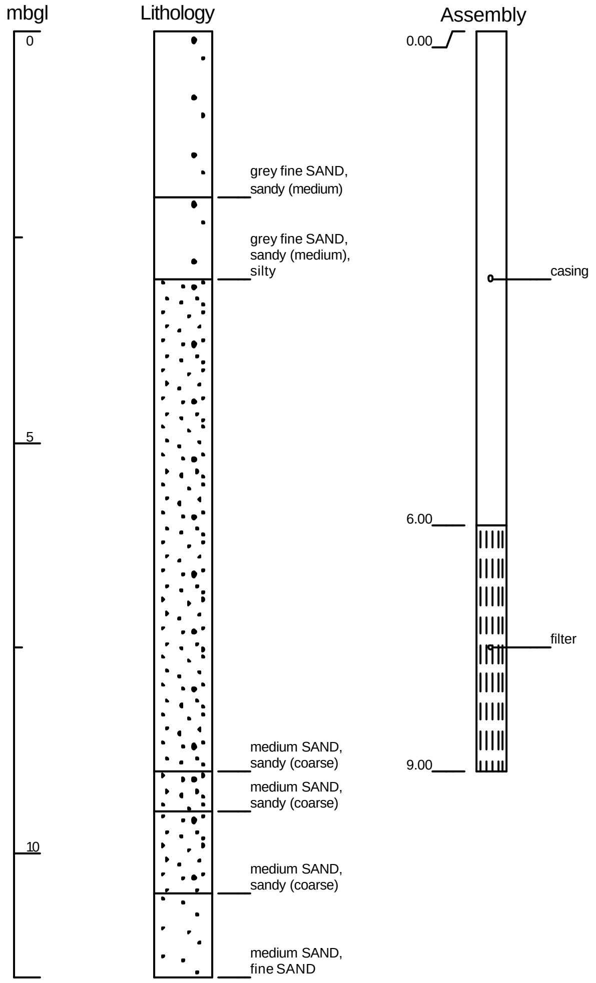
Device	Parameter	Accuracy	Measuring range
Eutech Cyberscan DO300	Diss. Oxigen (DO)	+/- 1.5%	0 - 20 mg/l
Eutech Cyberscan CON400	elect. Conductivity (EC)	+/- 1%	0.01 µS/cm - 199.9 mS/cm
Eutech Cyberscan 110	pH	+/- 0.01%	-2 - 16
Eutech Cyberscan 111	ORP	+/- 2 mV	+/- 2000 mV
Eutech Temp	Temperature	+/- 0.5 °C	-10 - 110 °C

Table a2 Detection tests, methods, parameters, accuracy and measuring range.

Name	Method	Parameter	Accuracy	Measuring range
Acidity test	titration	HCO_3^-	+/- 0.1 mmol/l	-
Nitrit test	colometric	NO_2	-	0.005 - 0.1 ppm
Ammonium test	colometric	NH_4	-	0.025 - 0.4 ppm
Sulfid test	colometric	HS^-	-	0.002 - 0.25 ppm

Table a3 Level logger specifications.

Device	Parameter	Accuracy	Measuring range	Measuring rates
Multi Sensor: Level and Temp logger (Solinst F30, M10)	water level	+/- 0.5 cm	- 10m below ground water level	0.5 s to 99 h
	temperature	+/- 0.005 °C	-10 to +40 °C	



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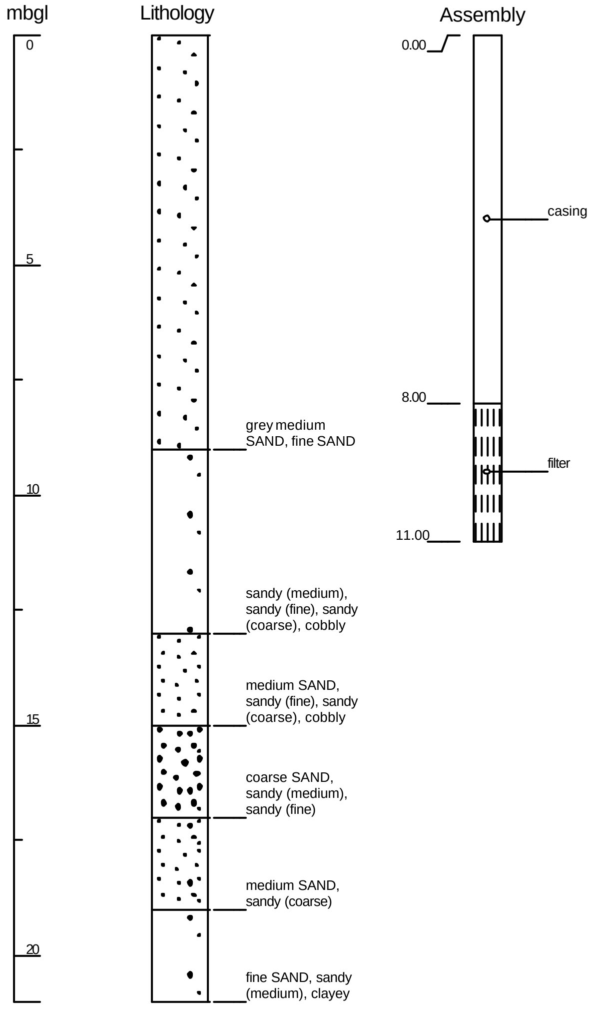
Project:	**TECHNEAU**		
Site ID	**PA-PZ-1**		
		X	716191
		Y	3192307
		Groundlevel	0.00m
		Total depth	11.50m

Figure a1



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Project:		
Site ID **PA-PZ-2**		
	X	716190
	Y	3192308
	Groundlevel	0.00m
	Total depth	21.00m

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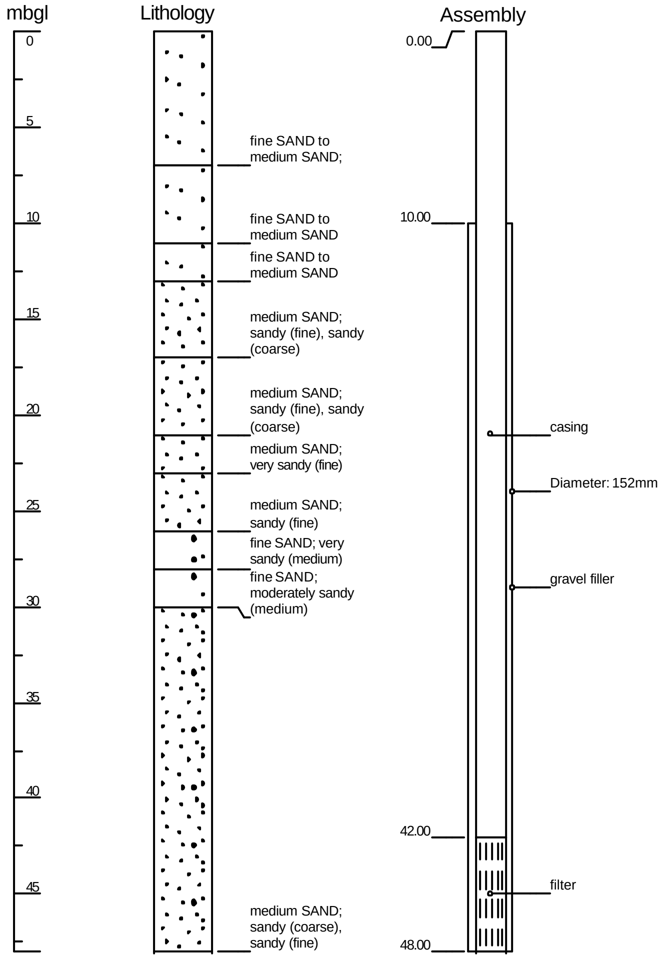
Figure a2



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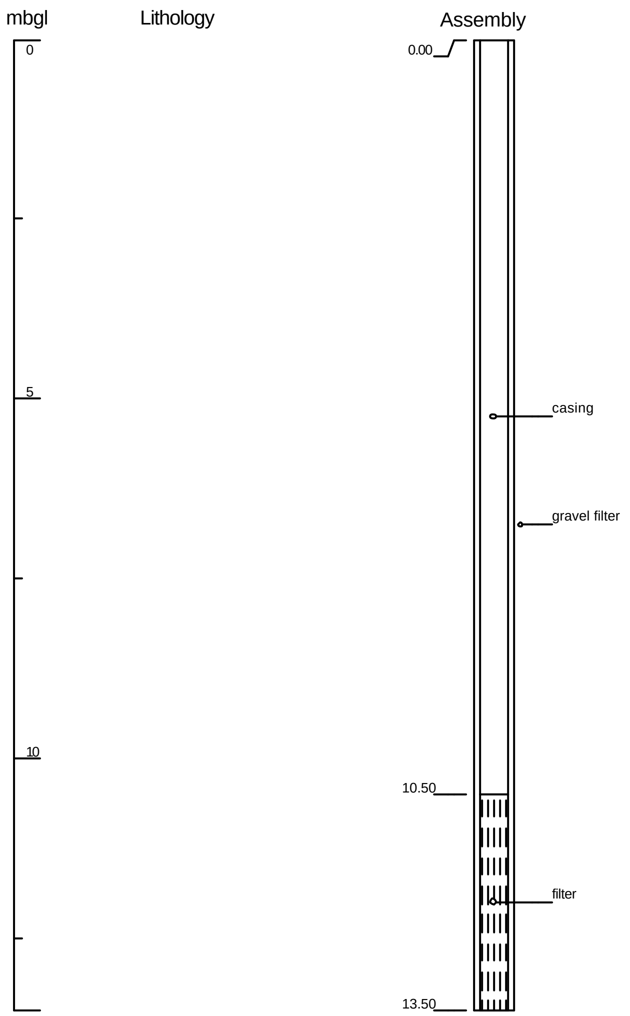
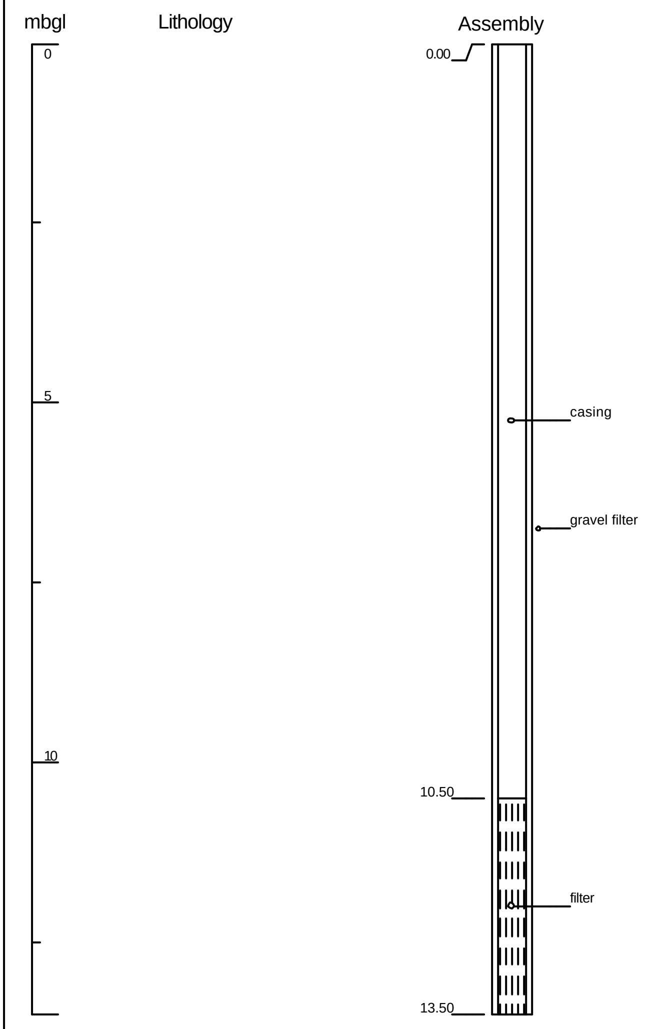
Project:	**TECHNEAU**	
Site ID	**PA-PZ-3**	
	X	716182
	Y	3192314
	Groundlevel	210.00m
	Total depth	48.00m

Figure a3



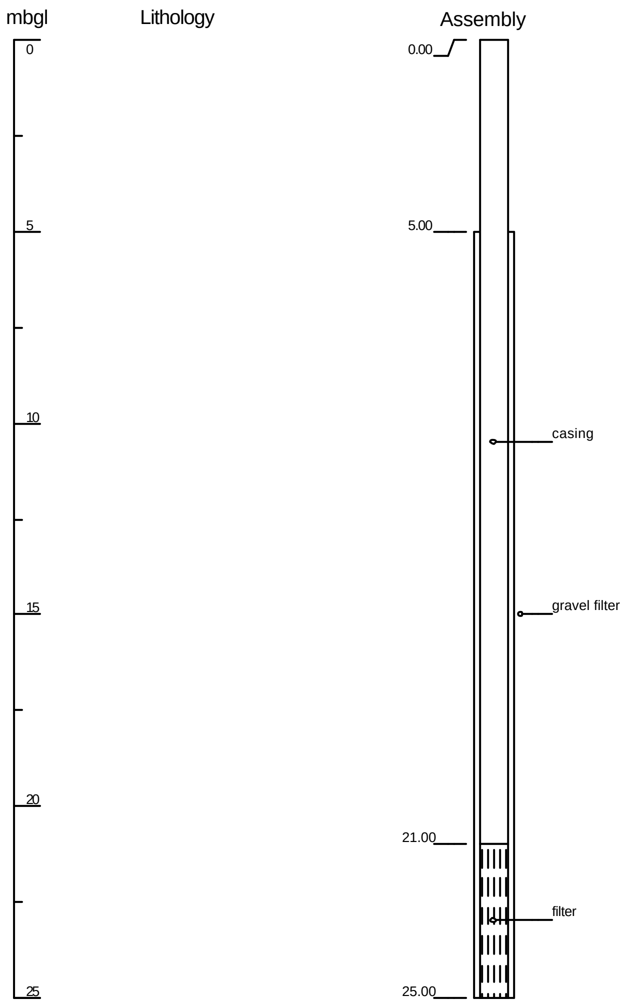
Project:		
Site ID **PA-PZ-4**		
	X	716199
	Y	3192299
	Groundlevel	0.00m
	Total depth	m

Figure a4



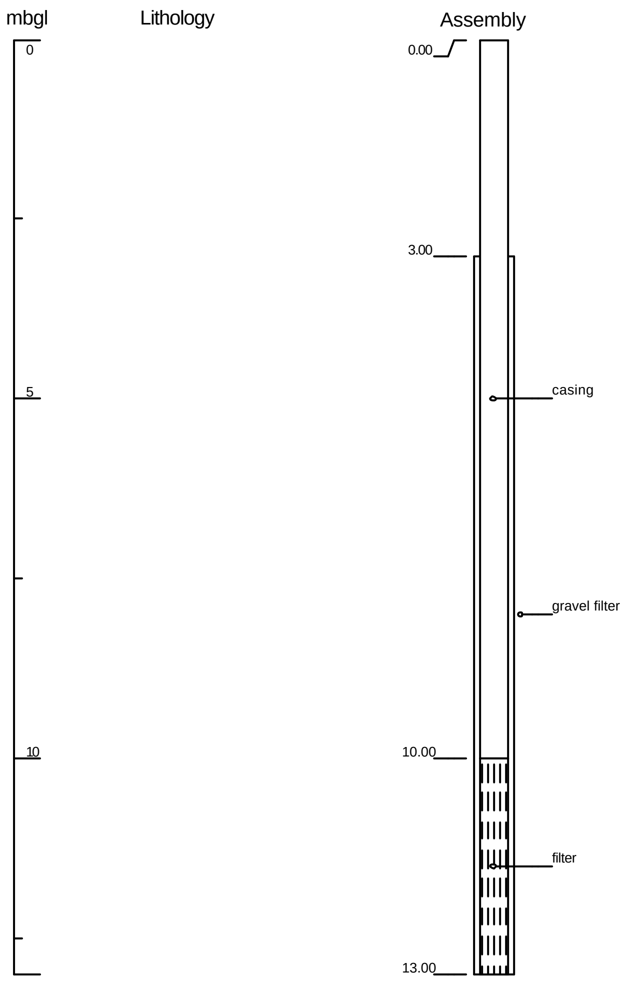
Project:		
Site ID	**PA-PZ-5**	
	X	716172
	Y	3192296
	Groundlevel	0.00m
	Total depth	m

Figure a5



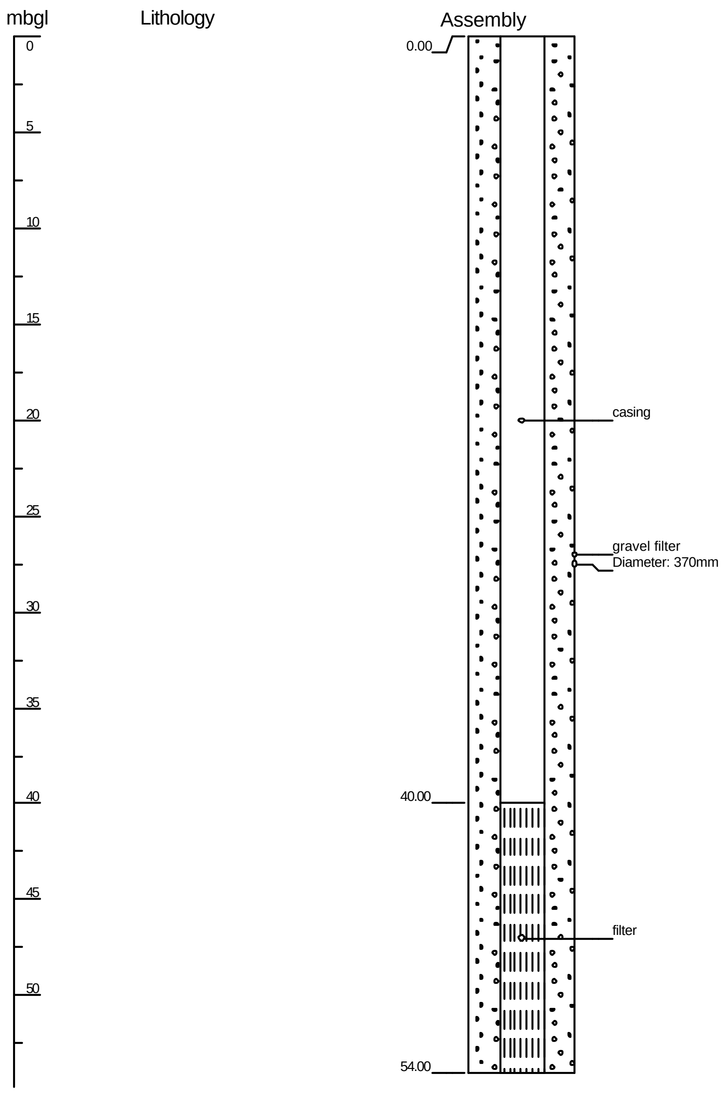
Project:	**TECHNEAU**		
Site ID	**PA-PZ-6**		
		X	0
		Y	0
		Groundlevel	0.00m
		Total depth	m

Figure a6



Project:		
Site ID	**PA-PZ-7**	
	X	716160
	Y	3192291
	Groundlevel	0.00m
	Total depth	m

Figure a7



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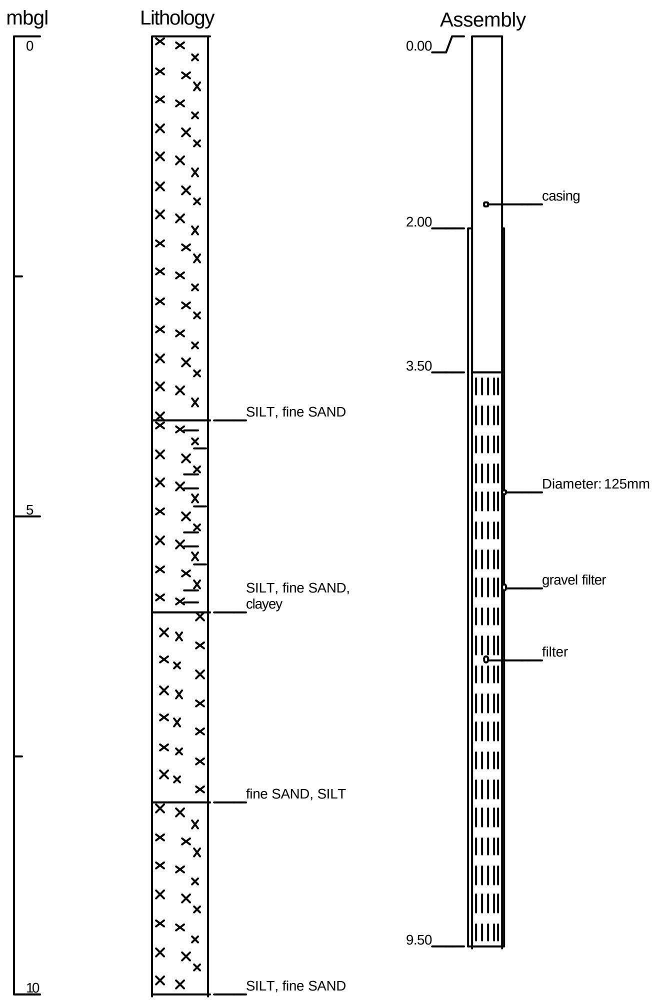
Project:		
Site ID **PA-TW**		
	X	716165
	Y	3192294
	Groundlevel	210.00m
	Total depth	m

Figure a8



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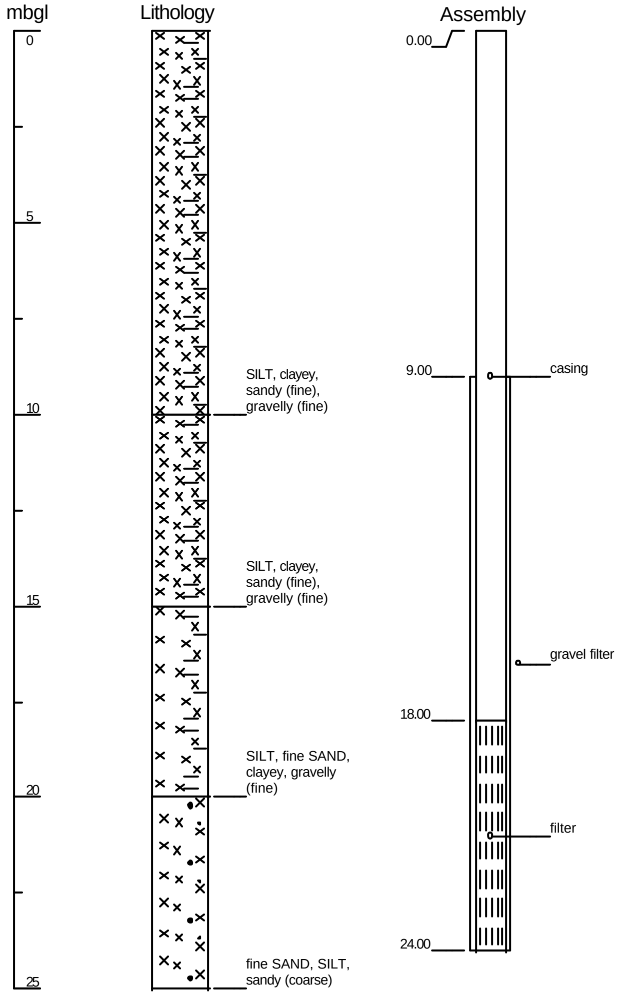
Project:	**TECHNEAU**		
Site ID	**NA-PZ-1**		
		X	686588
		Y	3157368
		Groundlevel	210.00m
		Total depth	10.00m

Figure a9



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Project:		
Site ID **NA-PZ-2**		
	X	686591
	Y	3157366
	Groundlevel	210.00m
	Total depth	25.00m

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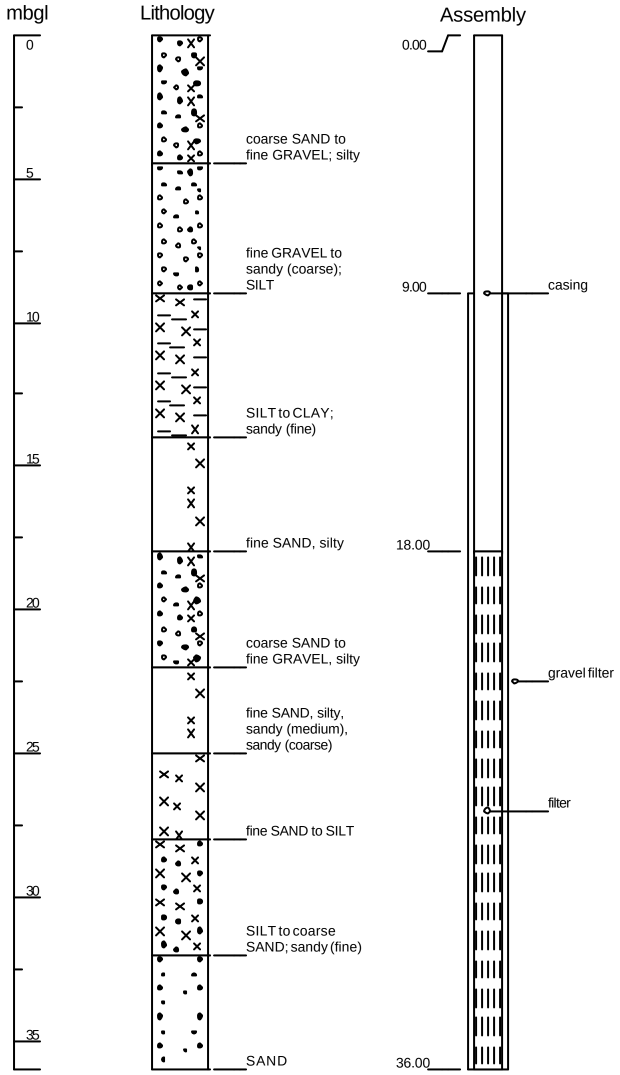
Figure a10



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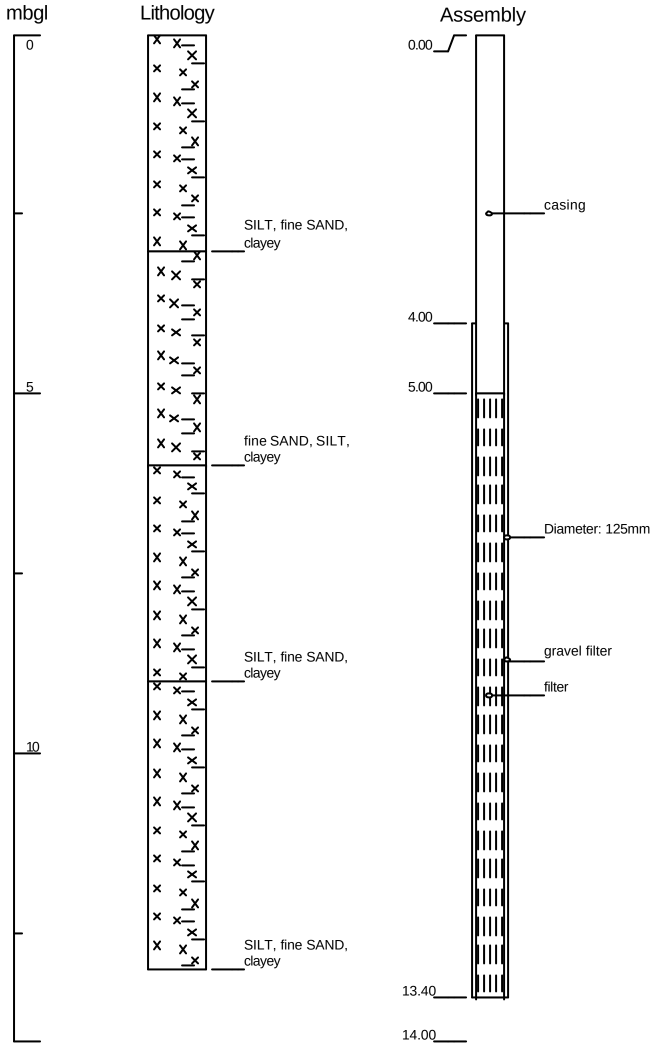
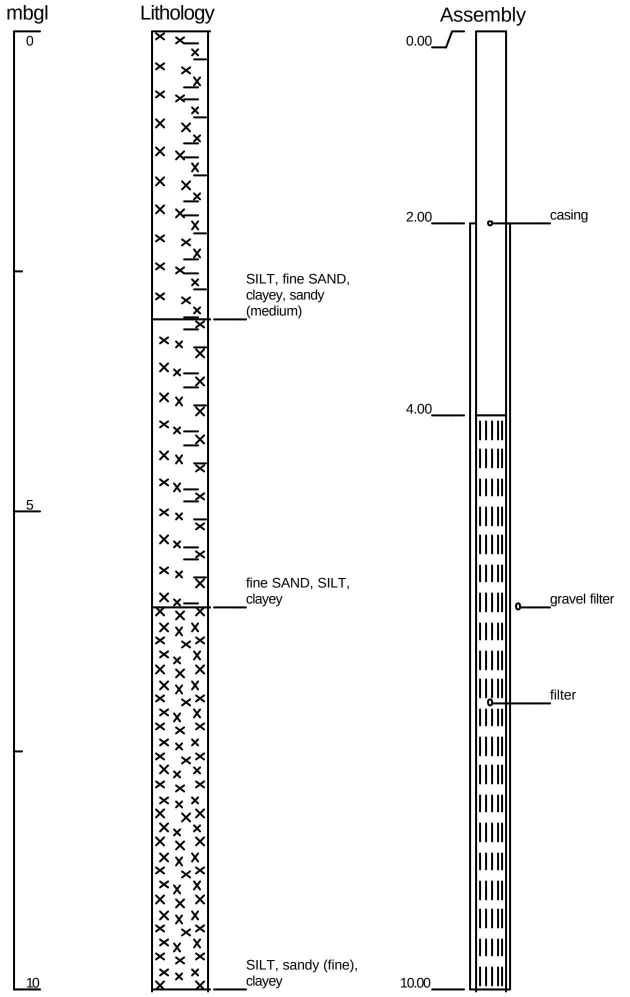
Project:	**TECHNEAU**		
Site ID	**NA-PZ-3**		
		X	686593
		Y	3157363
		Groundlevel	210.00m
		Total depth	36.00m

Figure a11



Project:	**TECHNEAU**		
Site ID	**NA-PZ-4**		
		X	686620
		Y	3157351
		Groundlevel	210.00m
		Total depth	13.00m

Figure a12



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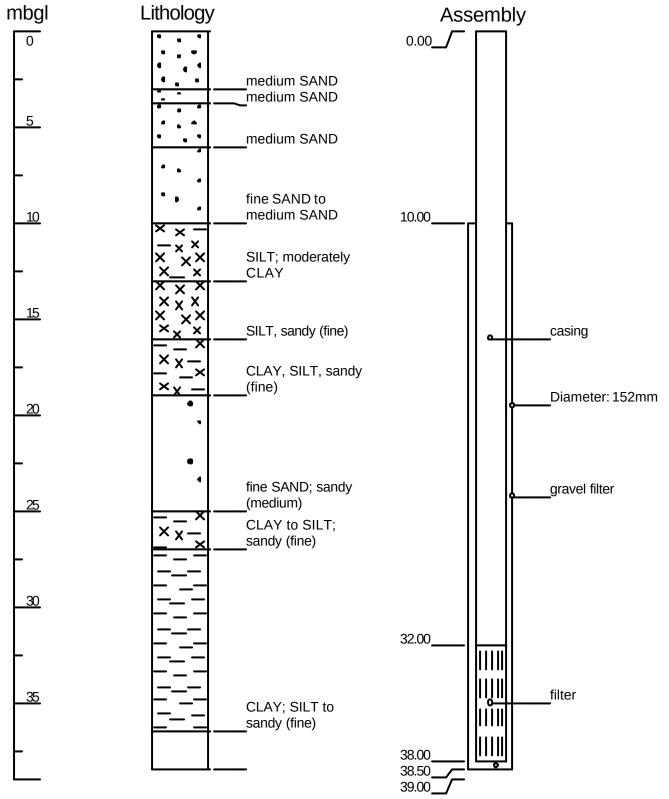
Project:			
Site ID	**NA-PZ-5**		
	X	686607	
	Y	3157401	
	Groundlevel	210.00m	
	Total depth	10.00m	

Figure a13



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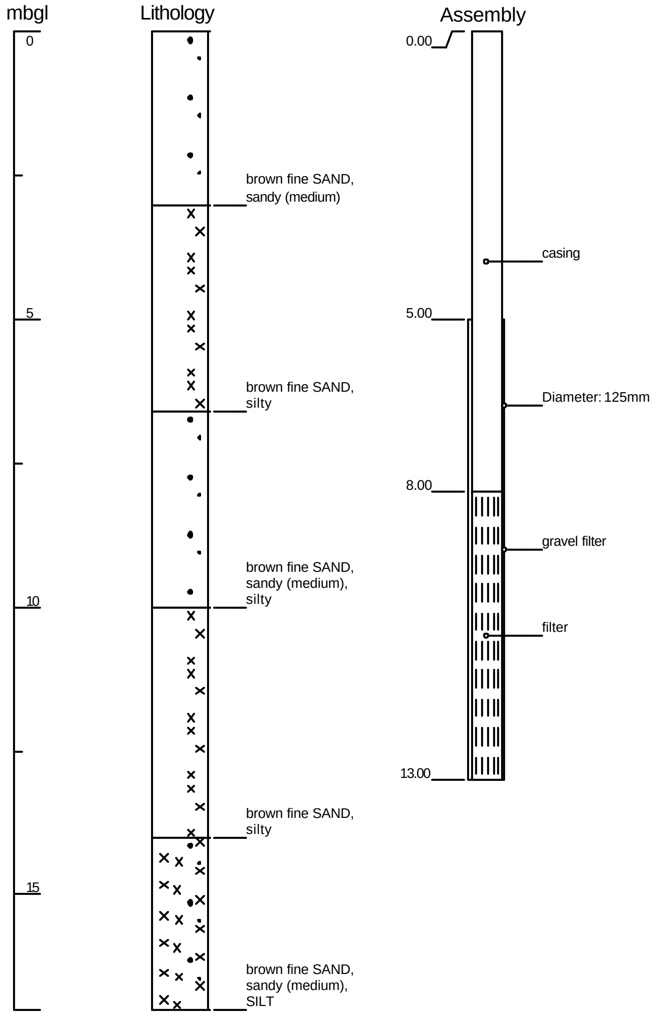
Project:	**TECHNEAU**		
Site ID	**NI-PZ-1**		
		X	721230
		Y	3166051
		Groundlevel	0.00m
		Total depth	38.50m

Figure a14



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Project:		
Site ID **NI-PZ-2**		
	X	721235
	Y	3166048
	Groundlevel	0.00m
	Total depth	17.00m

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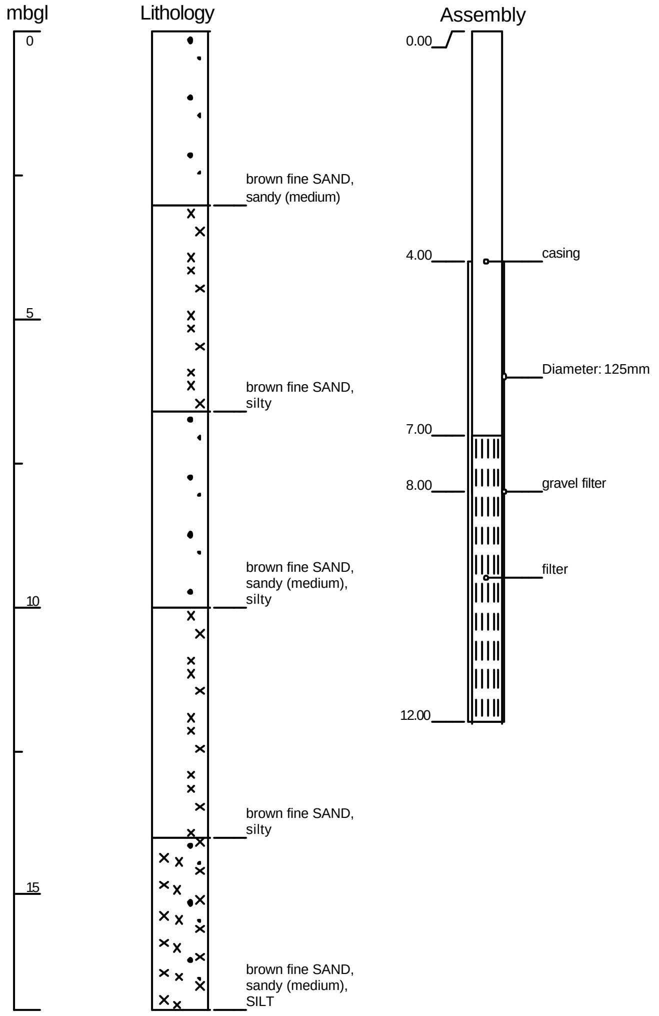
Figure a15



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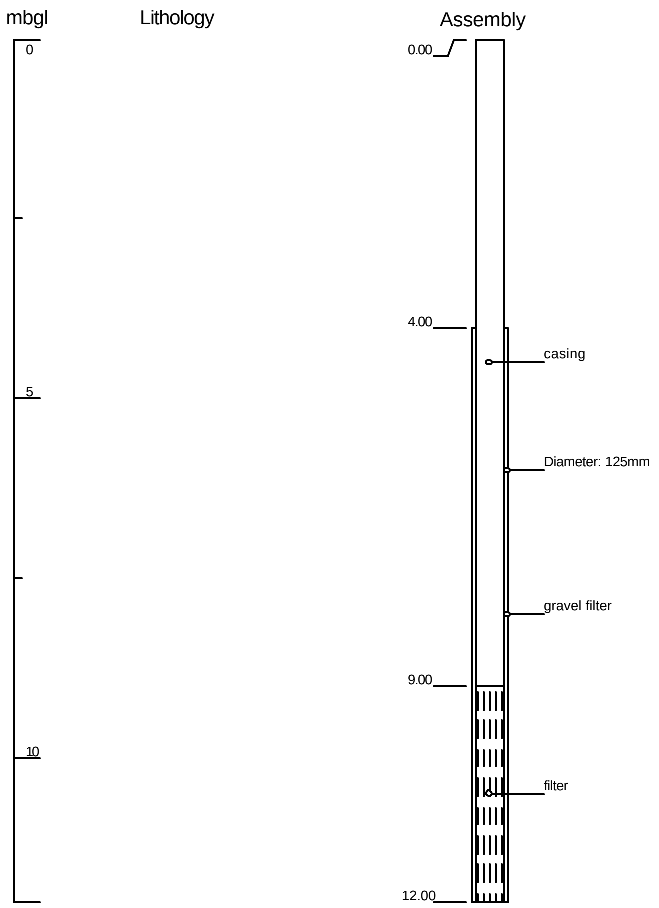
Project:	
Site ID **NI-PZ-3**	
	X 721235
	Y 3166048
	Groundlevel 0.00m
	Total depth 17.00m

Figure a16



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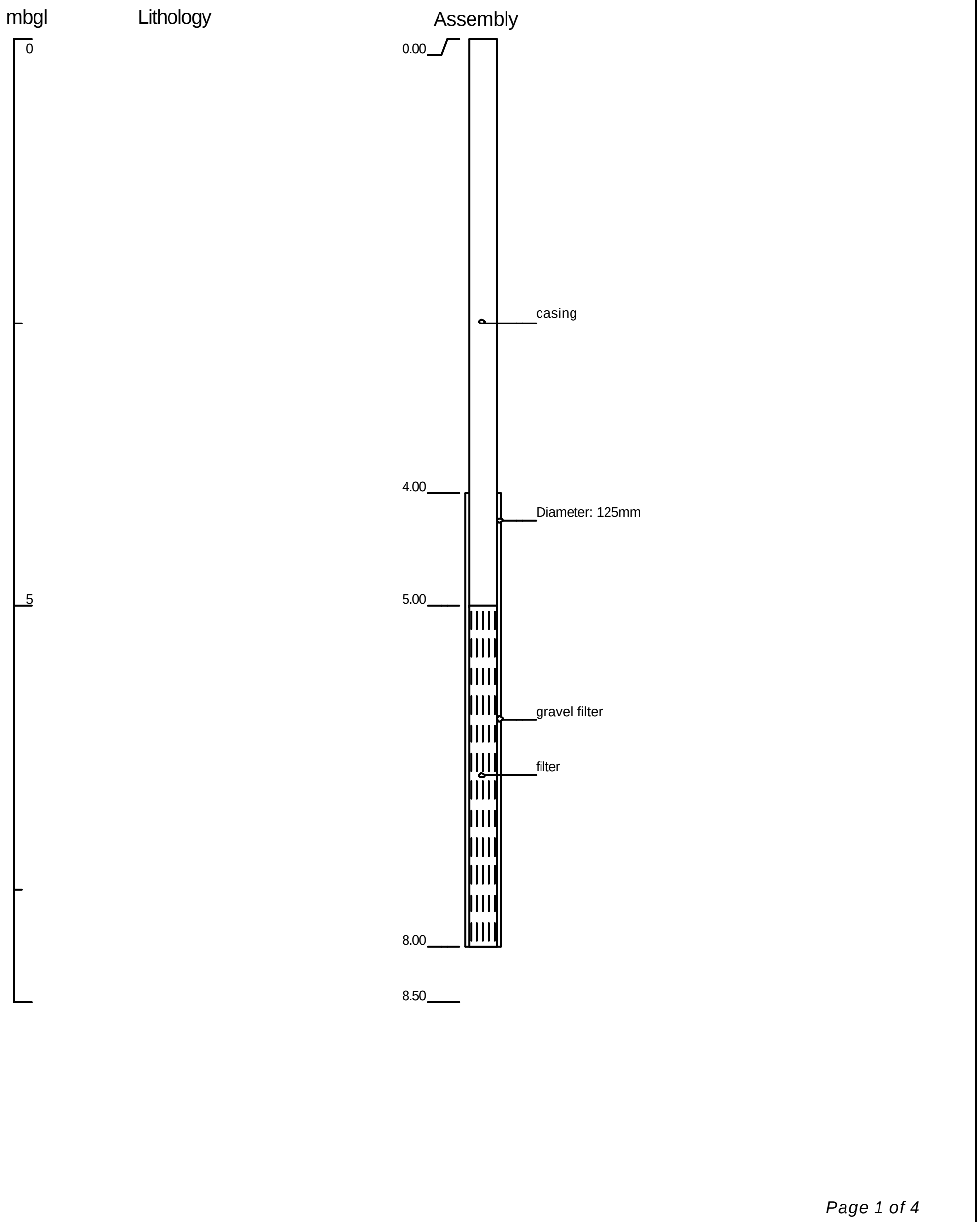
Project:	**TECHNEAU**		
Site ID	**NI-PZ-4**		
		X	721259
		Y	3166083
		Groundlevel	210.00m
		Total depth	m

Figure a17



Project:	**TECHNEAU**		
Site ID	**NI-PZ-5**		
		X	721259
		Y	3166083
		Groundlevel	210.00m
		Total depth	m

Figure a18

Project	Name	Site ID
Date	Sample ID	Site Discription
Weather	AirTemp [°C]	

	Time	Counter	
Start of pumping:			Type of pump(s):
End of pumping:			Discharge [l/min]:
tubeVol [L]:			Depth to water [m] (from top of piezometer) prior pumping

	0 min	*5 min*	*10 min*	*15 min*	*20 min*	stable
Depth to water [m] (from top of piezometer)						
el. Cond [µS/cm]						
WaterTemp [°C]						
pH						
ORP [mV]						
O_2 (%)						
O_2 (mg/l)						

colour:	odour:	turbidity:

	diluted --> diluted ppm		result [ppm]	*comments:*
NH_4^+	…… : …… -->	…….		
$NO2^-$	…… : …… -->			
HS^-	…… : …… -->			
Alcalinity --> mmol/l	…… : …… -->			

An (filtrated)	?		
Kat (filtrated)	?	plus HNO3	?
Isotopes	?		
T=Q*s [m^2/s]:		k_f=T/M [m/s]:	

comments: ……….

Figure a19 Sampling protocoll