Improvement of Groundwater Protection in Vietnam

Assessment of Groundwater Resources in Nam Dinh Province

Final Technical Report, Part A

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## Abbreviations

### General Abbreviations

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<tr>
<td>CWRPI</td>
<td>National Center for Water Resources Planning and Investigation</td>
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<td>CWRPIN</td>
<td>Northern Division of the National Center for Water Resources Planning and Investigation</td>
</tr>
<tr>
<td>DONRE</td>
<td>Department of Natural Resources and Environment</td>
</tr>
<tr>
<td>GEUS</td>
<td>Geological Survey of Denmark and Greenland</td>
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<td>GWIS</td>
<td>Groundwater Information System</td>
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<td>GWRA</td>
<td>Groundwater Resources Assessment</td>
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<tr>
<td>HUMG</td>
<td>Hanoi University of Mining and Geology</td>
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<tr>
<td>IET-VAST</td>
<td>Department for Environmental Quality Analysis, Institute of Environmental Technology, Vietnam Academy of Science and Technology</td>
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<td>IGPVN</td>
<td>Improvement of Groundwater Protection in Vietnam</td>
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<tr>
<td>INST-VAEC</td>
<td>Institute for Nuclear Science and Technology – Vietnam Atomic Environmental Commission</td>
</tr>
<tr>
<td>ITST</td>
<td>Institute of Transport Science and Technology</td>
</tr>
<tr>
<td>IUGS-ICS</td>
<td>International Union of Geological Sciences - International Commission on Stratigraphy</td>
</tr>
<tr>
<td>MONRE</td>
<td>Ministry of Natural Resources and Environment</td>
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<td>MOH</td>
<td>Ministry of Health</td>
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<tr>
<td>NDSO</td>
<td>Nam Dinh Statistics Office</td>
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<tr>
<td>N, S, E, W</td>
<td>North, South, East, West</td>
</tr>
<tr>
<td>PC</td>
<td>Peoples Committee of the Socialist Party of Vietnam</td>
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<td>PMU</td>
<td>Project Management Unit</td>
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<tr>
<td>RRD</td>
<td>Red River Delta</td>
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<tr>
<td>UNICEF</td>
<td>United Nations International Children's Emergency Fund</td>
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<td>WHO</td>
<td>World Health Organisation</td>
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## Technical Abbreviations

<table>
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<tr>
<th>Abbreviation</th>
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<tr>
<td>$A_0$</td>
<td>Initial carbon Activity (pmc)</td>
</tr>
<tr>
<td>AAS</td>
<td>Atomic absorption spectroscopy</td>
</tr>
<tr>
<td>API</td>
<td>Activity per inch (cps, counts per second)</td>
</tr>
<tr>
<td>ASTER</td>
<td>Advanced spaceborne thermal emission and reflection radiometer mission</td>
</tr>
<tr>
<td>BE</td>
<td>Barometric efficiency</td>
</tr>
<tr>
<td>CEC</td>
<td>Cation exchange capacity (cmol/kg)</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved oxygen (mg/L)</td>
</tr>
<tr>
<td>DOC</td>
<td>Dissolved organic carbon (mg/L)</td>
</tr>
<tr>
<td>EA-MS</td>
<td>Mass spectrometry equipped with elemental analyzer</td>
</tr>
<tr>
<td>EC</td>
<td>Electric conductivity ($\mu$S/cm; mS/cm)</td>
</tr>
<tr>
<td>EN</td>
<td>Electroneutrality (%)</td>
</tr>
<tr>
<td>IC</td>
<td>Ion chromatography</td>
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<tr>
<td>ICP-MS/-OES</td>
<td>Inductively coupled plasma mass spectrometry</td>
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<tr>
<td>ICP-OES</td>
<td>Inductively coupled plasma optical emission spectrometry</td>
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<tr>
<td>K</td>
<td>Hydraulic conductivity (m/s)</td>
</tr>
<tr>
<td>LMWL,GMWL</td>
<td>Local meteoric waterline, global meteoric waterline</td>
</tr>
<tr>
<td>LSC</td>
<td>Liquid scintillation chromatography</td>
</tr>
<tr>
<td>m bgl</td>
<td>Meter below ground level</td>
</tr>
<tr>
<td>m asl</td>
<td>Meter above modern sea level</td>
</tr>
<tr>
<td>n, $n_e$</td>
<td>Total porosity, effective porosity</td>
</tr>
<tr>
<td>S</td>
<td>Storativity, storage coefficient (-)</td>
</tr>
<tr>
<td>$S_s$</td>
<td>Specific storage (m$^{-1}$)</td>
</tr>
<tr>
<td>SRTM</td>
<td>Shuttle radar topography mission</td>
</tr>
<tr>
<td>TDS</td>
<td>Total dissolved solids (mg/L)</td>
</tr>
<tr>
<td>TOC</td>
<td>Total organic carbon (mg/L)</td>
</tr>
<tr>
<td>$v_D$</td>
<td>Darcy velocity (= apparent, macroscopic velocity; m/s)</td>
</tr>
<tr>
<td>$v_e$</td>
<td>Effective groundwater velocity (= seepage velocity; m/s)</td>
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<tr>
<td>VES</td>
<td>Vertical electric sounding</td>
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Further chemical abbreviations based on the nomenclature if the International Union of Pure and Applied Chemistry.
Summary

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Title: Assessment of Groundwater Resources in Nam Dinh Province – Final Technical Report, Part A.

Key words: Red River Delta, coastal aquifer, groundwater salinization, groundwater resources assessment, 3D-structural model, numerical hydrogeological model

In South of Nam Dinh Province, Red River Delta, fresh Pleistocene groundwater has been identified to exist next to brackish pore waters in the Red River area. Ongoing overexploitation of the fresh water results in decreasing GW heads up to 0.6 m/a and the development of a regional abstraction cone. Based on a new groundwater monitoring network quantitative hydrogeology methods were applied to study aquifer parameters, including simple models to determine aquifer storage based on observed barometric as well as tidal effects on groundwater heads. Interpretation of induction logging combined with diffusion modeling suggests vertical diffusion of primary paleo-sea water in Holocene sediments as a major source for high saline pore water in Pleistocene and Neogene aquifers. Hydrochemical and isotopic studies indicate adjacent Triassic rocks as the major source for fresh Pleistocene and Neogene groundwater. The conceptual model has been integrated into a 3D structural and numerical model. The study concludes into recommendations for provincial groundwater management. Lacking extraction data have been identified to be a major obstacle for water balance calculations and scenario analysis.

This report is divided into two parts, Part A presents a comprehensive conceptual hydrogeological understanding, focusing on genesis and availability of groundwater resources and Part B the design of a 3D structural and numerical hydrogeological model.
1 Introduction & Background

The recent growth of both population and economy in Viet Nam is based on the extensive exploitation of available water resources. Groundwater will become the major resource for the future water supply of Viet Nam, since surface water is vulnerable and increasingly affected by climate change, untreated sewage water and industrial waste water. Sustainable management of this finite resource is essential to life, development and environment.

During the last decades, the uncontrolled utilization and increasing exploitation of the finite groundwater resources in Viet Nam have resulted into several negative effects including:

- continuous declining of groundwater tables in a regional scale,
- salinization of coastal groundwater resources by seawater intrusion, and
- pollution by unsuitable handling of domestic, agricultural and industrial waste, waste water and sewage

The improvement of groundwater protection in Viet Nam (IGPVN) is essential for the social and economic development and the major objective of the IGPVN project by supporting the “National Center for Water Resources Planning and Investigation” (CWRPI) as well as the responsible provincial authorities (Department of Natural Resources and Environment, DONRE). Addressing this objective, it is essential to provide the technical fundament for groundwater management & protection and to advice responsible decision makers in frame of the Integrated Water Resources Management (IWRM) of Vietnam.

This final technical report documents the geoscientific as well as technical works carried out in Nam Dinh province, representing the pilot study area during the 1st project phase (June 2010 – February 2011). The Nam Dinh province is located at the southern border of the Red River Delta (RRD) in the North of Vietnam. Its groundwater resources represent all the negative impacts of overexploitation stated above. Therefore, CWRPI and BGR worked in close cooperation on a general assessment of groundwater resources in Nam Dinh in terms of quality and quantity based on both archive data as well as new own field studies. These data have been integrated into a hydrogeological model in order to fortify recommendations for local water management with scenario analysis.

This technical report “Assessment of Groundwater Resources in Nam Dinh Province” presents the comprehensive methods and outcomes in terms of two thematic parts: A Part A documents the applied quantitative methods and integrates the results into a conceptual hydrogeological model, comprising genesis and availability of groundwater resources with focus on groundwater overexploitation and salinization. Furthermore, a Part B presents the design of a 3D-structural as well as a numerical hydrogeological model including the simulation of groundwater extraction scenarios.

This on-hand Technical Report Part A is separated into 5 chapters. The 2nd chapter briefly presents the physical and socioeconomic frame of Nam Dinh Province. Chapter 3 documents
the general approach as well as the applied quantitative methods of field work and data analysis. In chapter 4, the results and outcomes are presented in the thematic subchapters Geology, Hydrogeology (Aquifer parameterization & GW dynamics) and Hydrogeochemistry (Aquifer characterisation, GW salinization, isotopic studies & GW quality). The subchapters of chapter 4 conclude in “grey boxes” with lessons learnt for future technical studies as well as groundwater management in Nam Dinh. Chapter 5 provides an extended summary comprising the major outcomes of Part A and Part B and draws general conclusions and their implications for groundwater resources assessment in Nam Dinh. Finally, the chapter 6 translates the technical and scientific outcome into implications for groundwater management in Nam Dinh.

Since the 1990s, groundwater resources in the RRD including Nam Dinh area was subject of mapping and exploration projects carried out by governmental authorities. Moreover, Vietnamese universities have published several scientific studies about groundwater related issues in Nam Dinh and upstream areas, partly in cooperation with international partners. Therefore, a comprehensive number of previous studies provided a basis for this report. All used references are cited in the coming chapters and provided in chapter 8. As a summary, the most relevant information sources about hydrogeology and groundwater resources in Nam Dinh are namely:

- Geological Mapping of Nam Dinh – Thai Binh, 1:50 000 (NGUYEN VAN CU et al. 1996)
- Hydrogeological Mapping 1:50 000 with Explanations (NGUYEN VAN DO 1996a, b)
- Reports of the Northern Division of CWRPI (NGUYEN VAN DAN et al. 2009)
- Vietnamese scientific studies published in national journals (e.g., DOAN VAN CANH et al. 2005; LE THI LAI et al. 2005; LE THI LAI et al. 2003)
- International journals and scientific studies (e.g. HOAN V. HOANG et al. in prep.; HOANG DUC NGHIA 2008; LARSEN et al. 2008; TANABE et al. 2003a)
- National Groundwater Monitoring Well Data from 1995-2010, collected by the National Center of Water Resources Planning & Investigation (CWRPI, unpublished)

It must be stated, that at the beginning of the IGPVN activities, the provincial DONRE Nam Dinh who is responsible for groundwater management on the provincial level was not aware of the relevant information sources and their outcomes. Therefore, the IGPVN project is not only reviewing the scattered data sources, transferring into joint digital form and integrating them into a joint picture regarding a groundwater resources assessment. Furthermore, it has also the task to facilitate the transfer of already existing as well as new expertise to national as well as local decision makers.
2 Physical Setting of Nam Dinh Province

The Nam Dinh province has a NW-SE extension of 46 km and a SW-NE extension of minimum 16 km in the central part and maximum 60 km at the coastline to the Gulf of Tonkin and an area of about 1652 km$^2$. Nam Dinh represents the southernmost edge of the RRD, which is located on the western coast of the Gulf of Tonkin in the South China Sea. Therefore, its physical setting is connected to the subsidence of the Red River basin and development of the delta system.

The Red River (Song Hong) is about 1,200 km long, originates in the mountains of Yunnan Province in China and enters Vietnam close to the Laos border. Its two main tributaries, the Song Lo, also called the Lo River or the Clear River, and the Song Da, also called the Black River contribute to the high water volume of the Red River. The river course and the narrow drainage area is regulated by the NW–SE aligned Red River fault system.

The pre-cenozoic basement of the NW trending Red River basin began to subside in Neogene time, initiated by the strong uplift of the Proto-Himalayan mountain chain. High erosion rates resulted in the mobilization of huge amounts of material, which was collected by the tributaries of the major receiving river systems and transported to the Gulf of Tonkin; recent erosion rates reach approximately 130 Million tons of sediments per year (TANABE et al. 2003b). During millions of years, deposition and accumulation at the river mouth in combination with ongoing subsidence of the Red River basin finally resulted in the formation of the huge River Delta complex.

The axis of the Red River basin is marked by the Red River fault which splits into two branches (Figure 1), the northeastern Song Chay fault, and the southwestern Song Hong (Red River) fault (SEARLE 2006). These two faults bound the Ailao Shan–Red River shear zone. The central basin axis contains more than 3 km of Neogene sediments along a narrow 30-50 km wide graben (MATHERS et al. 1996; MATHERS et al. 1999). The graben is thought to have subsided totally about 6 km over the last 50 million years resulting in a maximum long-term subsidence rate of the 0.12 mm/a (MATHERS et al. 1996) of the central part of the basin.

However, other authors estimate that fault movements are considered to be

![Figure 1: Sketch map showing the location of the RRD (square) in the Red River (Song Hong) basin as well as approximate area of the drainage area along the Red River fault system (TANABE et al. 2003b).]
2. Physical Setting of Nam Dinh Province

minor at least since the late Miocene. RANGIN et al. (1995, in SEARLE 2006) suggested minimal or no post-Pliocene displacement based on offshore seismic data from the extension of the Red River fault into the Gulf of Tonkin. SEARLE 2006 estimates that left-lateral shearing along the Red River fault in North Vietnam initiated around 21 Ma and ended at 5.5 Ma.

Geomorphology of the RRD plain can be divided into wave-, tide-, and fluvial-dominated systems on the basis of surface topography and hydraulic processes (Figure 2, MATHERS et al. 1996; MATHERS et al. 1999). Except of the Red River bank area, large parts of the geomorphology of Nam Dinh is supposed to be wave-dominated.

2.1 Soils & Land use

The soils of the RRD are generally fertile and have been utilized since ancient times for intense agriculture with predominance of rice paddy cultivation. Traditionally, the repetitive flooding events regularly added nutrient rich silt and clay to large areas of RRD. Dykes and other flood prevention measures result in the increasing use of chemical fertilizers. According

Figure 2: Quaternary geology and topography of the Song Hong delta and adjacent areas (modified after TANABE et al. 2006), including location of Nam Dinh province (blue). Thin dotted lines indicate the geomorphological division of the delta plain into fluvial-, tide-, and wave-dominated systems according to MATHERS et al. 1999).
2. Physical Setting of Nam Dinh Province

To LEHMUSLUOTO 2007 large areas of the RRD including Nam Dinh province are covered with alluvial fluvisols, moreover with saline soils and acid sulphate soils.

Typically for the RRD area, Nam Dinh is basically an agricultural dominated province. Paddy rice with 2 harvests per year represents the predominant crop with more than 58% coverage of the whole area (Figure 3). For centuries, flood control has been an integral part of the delta’s culture and economy. An extensive system of dykes and canals has been built to irrigate the paddy fields with river water from through to contain the Red and the Dao River. Furthermore, fish and shrimp aquaculture using fresh and brackish water is widespread with almost 5% area coverage. Other annual crops have only minor relevance with less than 2% coverage. Urban and village area represent about 16 % of the total area. In total about 74 % of the province area is temporarily flooded by paddy irrigation, aquaculture farming and other water bodies which is expected to have relevant impact for the subsurface water balance.

Figure 3: Land use distribution in Nam Dinh province, status 2007. Legend lists only land use types covering above one percent of total province area.
2.2 Climate, Rainfall and Runoff

2.2.1 Climate

The northern part of Vietnam has subtropical monsoon climate, with humidity averaging 84% throughout the year. This typical North Vietnamese climate dominates the microclimate of Nam Dinh province with bit cooler temperatures and a higher humidity due to its vicinity to the sea. Below, long term climate parameter are presented following NGUYEN VAN DO 1996a in comparison with the data from the climate station Vu Ly for the year 2007 (Figure 4).

During the winter or dry season (November - April), the monsoon winds usually blow from the northeast along the China coast and across the Gulf of Tonkin, picking up considerable moisture. Consequently the winter season in most parts of the country is relatively dry in comparison to the rainy or summer season. Lowest daily average temperatures are met in January and February with 10 to 13°C and average humidity can be “relatively low” with 94% (November-December), but also reach highest average humidity with up to 98% (January-March). The monthly average rainfall varies between 86.9 and 118 mm.

The southwesterly summer monsoon from May to October is associated with hot temperatures and heavy rain falls. Maximum daily average air temperature occurs generally in June and July varying from 29 - 31.2°C. The lowest relative humidity is 86.5% and the highest relative humidity is up to 92% in July, while the monthly average rainfall lies between 87.1 within 427.6 mm (see also Figure 4).

The climate data from Vu Ly station close to the sea (UTM WGS84 635985 E, 2224922 N) show the development of the potential evaporation throughout the year. Where open surface bodies, such as channels or irrigated paddy fields exist, the evaporation is quite intense throughout the year. In other areas, evaporation is limited in the dry season (November –
April) by lower rainfall.

2.2.2 Surface Water Bodies

Nam Dinh province is covered with a dense surface water network consisting of natural rivers and artificial channels with a general flow direction from NW to SE. The channel network is increasing in density towards the coastal Nam Dinh area and has crucial relevance for irrigation of paddy fields and other agricultural areas with river water as well as discharge of sewage and waste waters to the sea.

Four major rivers are located within or at the border of Nam Dinh, the Red River along the NW border of Nam Dinh with his river mouth at the Ba Lat Estuary, the Đào River connecting the Red and the Đáy Rivers (SW border of Nam Dinh) and the Ninh Cơ River with its river mouth to the sea at Lạch Giang estuary.

From Nam Dinh city to the Red River mouth, the Red River bed has 54 km lengths and is estimated to be 400–500 m wide and about 10-15 m deep. The water discharge of the Red River varies strongly in terms of the season. The discharge at Ha Noi station reaches a maximum in July–August (about 23 000 m³/s) and a minimum during the dry season in January to May with typically 700 m³/s (TANABE et al. 2003). Salinization of the Red River due to tidal fluctuation has been studied first by NGUYEN VAN DO 1996a. During dry season and tidal high stand, elevated salinity has been observed up to 4.5–5 km inland from the Ba Lat estuary.

The Day River follows the W border of Nam Dinh with 400-500 m width and 45 km length, coming from the Triassic limestone recharge area in Ninh Binh province. Maximum flow rate has been observed in August with 3110 m³/s; lowest flow rate can be almost zero (no flow) in December and January, yearly average is 813 m³/s. Although this river is tidal influenced, salinity monitoring has shown that total salinity is generally <1g/l (NGUYEN VAN DO 1996a). Thus, the fresh-salt water boundary is estimated to be close to the sea, which can be explained by a high hydraulic gradient and flow rate of the river. The high hydraulic gradient is caused by a W tributary of the Day River, the Boi River, who is discharging a large mountainous area in the NW of Nam Dinh Province.

2.3 Population, Economy & Water Supply

Latest statistical data published by Nam Dinh province state a total population of 1 826 300 (2009) persons and a population density of 1105 persons per km². About 16 percent of population live in Nam Dinh city (244 000; 5276/km²) and 84 percent of remain population live in 9 other districts with an average population density of <1000/ km² (NDSO 2010). Since 2005, the fertility rate is reported to be quite stable within 15-16 ‰, corresponding to a mortality rate of 5.8 ‰. The Viet people represent by far the majority of population in Nam Dinh, only less than one per cent belong to 3 other minorities, the Tay, the Muong and the Hoa.
During the French occupation, the province was famous for textile industry and manufacture. Nowadays, Nam Dinh recently established 7 industrial parks which are located along the main roads and ports. These industrial parks accelerate the economic development of Nam Dinh and have an enormous need of natural resources such as fresh water and waste water disposal. Therefore, the industrial parks enormously increase the pressure to the environment given the fact that water consumption as well as waste water treatment and disposal is not sufficiently regulated.

Official statistical data about centralized water supply demonstrate the increasing water demand in Nam Dinh province (Figure 5), in both central communal as well as decentral private water supply. The origin of water supply (surface, groundwater) is not distinguished in these data, furthermore, any water supply operated by commercial companies (industrial, agriculture, aquaculture) have been neglected. Based on own observations and interviews, the majority of the communal water supply is based on surface water using simple treatment techniques, if any. The private households generally take their water from tube wells screened in 50 to 120 m depths.

Please note that the figures presented here (Figure 5) are based on statistical data published from Nam Dinh authorities. Further insight into extraction quantities from private household wells, based on previous studies, is provided in frame of the numerical modeling (see this report, Part B). Please note, that due to the sparse and contradicting data base about groundwater extraction in Nam Dinh province, IGPVN project is preparing a field survey including a questionnaire of private households in order to get up-to-date data about the groundwater use and extraction habits.

Figure 5: Bar chart showing official data for communal and private water supply (ws) in Nam Dinh from 2005 to 2009 (NDSO 2010).
3 General Approach & Applied Methods

Principally, the necessary steps resulting in the final goal to advise water policy based on a reliable groundwater assessment and scenario analysis comprises multiple activities on principally four working levels (Figure 6):

I. Comprehensive data collection & continuous monitoring,
II. Data management & processing,
III. Evaluation & analysis using conceptual, analytical and numerical modeling techniques and
IV. Drawing recommendations and advising water policy.

This outline does not only represent the general approach of the IGPVN project in case of the pilot project area but also mark the general steps which need to be addresses prior to advise water policy. The national or provincial state authorities (MONRE, DONREs) who are in charge of (ground-) water management clearly need to assign roles and responsibilities of the subordinate authorities in order to fulfil their roles on the different geotechnical as well as management levels.

The initial step of each groundwater resources assessment study includes always a comprehensive desktop study addressing archive data sets, reports and maps from previous studies as well as national and international publications (Working level I). Diverse and heterogeneous data themes and sources need to be considered in order to obtain a robust assessment of available groundwater resources. The data extracted from these sources are supplemented by own field studies and monitoring works. Prior to further analysis the

Figure 6: IGPVN approach and work flow resulting in a Groundwater (GW) Resources Assessment and recommendations for GW management (Design: H.J. Sturm, BGR).
collected data need to be homogenized, processed and integrated into a joint hydro-geo
database (working level II). Based on the database, further integrated data analysis and
interpretation as well as modelling works (Working level III) are carried out in order to design
and submit recommendations groundwater management (Working level IV).

A comprehensive Hydro-Geo Database is considered to be useful only when it can easily be
distributed or can be accessed by other stakeholders and decision makers on a national and
provincial level. Therefore, the IGPVN project supports a joint and MONRE wide hydrological
and -geological database in cooperation with the BTC and DWRM (Clos, in preparation).

The following subchapters contain a description of applied methods of technical field work
and data analysis. Further insight into data evaluation and applied modelling techniques are
provided in frame of Part B of this report, concerning 3D structural and numerical
hydrogeological modelling.

3.1 Monitoring Well Construction

The operation of a regional monitoring network is a premise for a reliable and up-to-date
groundwater database with the aim to characterize the existing groundwater resources and
with special respect to their spatial heterogeneity. In the pilot-study area Nam Dinh Province,
the already existing national monitoring network is installed in 5 locations consisting of 9
monitoring wells, which are screened in the Holocene (qh, n=5), the Pleistocene (qp, n=3)
and one in the “Pliocene/Neogene” aquifer (n/m4). These national monitoring wells are
aligned on a NW-SE directed profile (Figure 7) and are manually operated by the Northern

Figure 7: Geological sketch map with location of National Monitoring Wells (Q92, Q107-Q111) and
New Monitoring Wells (Q220-Q229) installed by IGPVN project in Nam Dinh Province.
Division of CWRPI (CWRPIN) since 1995. Nevertheless, this valuable data source is not satisfying in order to assess the groundwater resources considering all relevant aquifers as well as their spatial heterogeneity.

In order to complement the already existing monitoring network single- as well as multilevel monitoring wells have been installed in 10 locations (Q220 – Q229) with altogether 23 wells and a maximum depth of 160 m below surface, accessing the three major aquifers of Holocene (qh1) and Pleistocene age (qp2, qp1) and the Triassic aquifer. Additional observation wells have been installed at site Q227 in order to observe the aquifer response and calculate hydrogeologic parameters while performing pumping tests. The map in Figure 7 shows locations of old and new monitoring wells, a list of their depth, location and coordinates can be found in Annex 1. The technical details of drilling works and well design are described in CWRPI 2009, a brief summary is provided below.

### 3.1.1 Monitoring Site Selection

Intensive negotiations with representatives of the DONRE departments of Nam Dinh province and its districts as well as the leaders of the communal Peoples Committees (PC) were necessary in order to receive permissions and to select a specific drilling location. Land requirements comprise temporarily 100 -150 m² during the drilling works and permanently 4-6 m² for the operation of each monitoring site. The drilling sites have been selected according to the following crucial criteria:

- **Hydrogeologic criteria**: access aquifers most relevant for water supply, complement existing monitoring sites with respect to the spatial heterogeneity of aquifers,
- **Logistic criteria**: availability of public land, accessibility by heavy vehicle (drilling, sampling, pump test), absent groundwater extraction in vicinity
- **Economic criteria**: available budget limits the density of monitoring network

In some cases, it has been time consuming to select appropriate monitoring locations in coordination with local authorities of the Peoples Committee (PC) and Provincial Department of Natural Resources and Environment (DONRE).

### 3.1.2 Drilling Works and Well Design

In each location drilling works have been carried out in three steps, (1) Exploration drilling, (2) well drilling and casing and (3) well flushing, more technical details are provided in CWRPI (2009). The drilling and well installation works were carried out by CWRPIs subdivision of Water Resources Planning and Investigation No. 47 using drilling rigs URB-500 and URB-ZAM (Russia). Boreholes up to 200 m bgl have been drilled in rotary drilling technique. Sediments and rocks varied from Holocene and Pleistocene unconsolidated sediments to semi-consolidated siltstone (Neogene) and sandstone (Triassic). During the drilling works, the bore hole was stabilized using Bentonite drilling mud with 1.1 to 1.3 g/cm³ density.
An exploration borehole at each monitoring location was drilled to characterize the local lithology including exact depth of groundwater bearing strata as well as to collect drilling cores. The exact position of screen was defined accordingly. A sediment catcher/tube for sampling has been used with the requirement to receive at least 70% of the total core material. Only in high sorted sand layers less than 70% has been recovered. Subsequently after collection, the sediment cores have been stored into core boxes and properly marked for later sampling and cross-checking with in-situ equipment. The sediment lithology was described by a technical geologist, who was part of each drilling team.

The preliminary well design including exact screen depth was adjusted based on local geological and lithological setting. Following Vietnamese standard, sump casing, screen and casing tube consisting of PVC tubes with outer diameter of 90 mm and thickness of 5 to 6 mm. In some cases (e.g., Q227a, Q222) a bigger casing diameter has been chosen above the screen to improve borehole stability. Slots in screen tubes had about 0.3 mm thickness. Well installation took place after drilling of larger diameter boreholes (usually 2-3 times of casing diameter), so that borehole filling by gravel, sand and clay can be done easily. To avoid collapse of borehole, a supportive steel casing was installed in the uppermost part of the borehole. After installation of the PVC casing, boreholes have been flushed to remove remaining drilling mud and debris in the well. Subsequently, the space between borehole wall and screen was filled with coarse sand/ fine gravel in the whole water bearing horizon. Filling material around screen was chosen to be from 1 to 3 mm in diameter depending on grain size of water-bearing horizon. Above the screen, the outer borehole was sealed with bentonite.

After installation, wells were developed using an airlift pump (5 to 10 atm) in order to recover the permeability in the contact zone of well and aquifer. The suction and washing work has been carried out from upper to lower section. After pumping in several 10 minute intervals, water was clear and drilling debris was removed from wall and bottom of boreholes and screen. Finally the pump was lowered so that maximum output of water was reached from the well. After finishing, recovery of water level and the depth of bore hole were measured. Massive concrete basement contains a benchmark for geodetic measurements and protects the well from violation (e.g., Figure 8).

### 3.1.3 Geophysical Well Logging

Collecting high quality sediment cores with the applied simple rotary drilling technique is not easy due to core compaction or loss, especially in coarse grained unconsolidated sediments. Geophysical well logging is a common tool to obtain information of the geological strata in the borehole. The results have been used as a quality control of the lithological description by the technical geologist in field and have the potential to identify further physical properties of aquifer units.

The geophysical well logging of the monitoring stations has been carried out in two steps. Initially after completion of drilling works in December/January 2010 by the Northern Division
of the CWRPIN (Teamleader Pham Duy Trinh) has been carried out in the boreholes prior to casing installation in the fluid filled borehole where the fluid electrically couples the electrodes to the neighboring strata. In March 2011, a second field campaign has been carried out by the Hanoi University of Mining and Geology (HUMG, Teamleader Hoang V. Hoan) in cooperation with the Geological Survey of Denmark and Greenland (GEUS), see also Table 1. Annex 2 provides a documentation of the graphical logging results measured in March 2010, which are interpreted and discussed in chapter 4.3.2.

The logs are usually run up-hole to assure constant tension in the cable and better depth control. Nevertheless, the fluid conductivity logging (March 2010) has been performed down-hole to measure salinity of the undisturbed water column. Generally, several up- and down-hole logs have been performed per drilling site. In some cases of equipment failure during the up-hole run(s), a down-hole measurement was considered to be more representative. A caliper log has not been carried out in the open borehole due to the risk of borehole collapse. Therefore, correction of logs influenced by the hole diameter, such as natural gamma, was not possible.

### 3.1.3.1 Electrical Resistivity

Electrical resistivity logs are restricted to fluid filled unlined boreholes, where it measures the electrical resistivity of the formations in the wall of the borehole. They are used to distinguish aquifer and aquitard horizons and furthermore, can help to identify aquifer properties. Several factors determine the electrical resistivity measurement, such as porosity, clay content and the conductivity of both, the fluid column and the pore water. The resistivity log types applied in this study are:

**Single Point resistance (SPR) log:** The resistance is measured between a single electrode on the probe and another electrode at the well top. The SPR is difficult to use quantitatively, but has very good vertical resolution in narrow boreholes, whereas in wider wells its utility is limited (Mistear et al. 2007).

**Normal electrode configuration (R8, R16, R32, R64):** In this configuration, current passes between an electrode A at the Base of the probe and an electrode B at the top of the probe. Potential difference is measured at an electrode M at a distance of 8 inches (203 mm, R8),

<table>
<thead>
<tr>
<th>Well logging campaign</th>
<th>January/ February 2010</th>
<th>March 2011</th>
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</thead>
<tbody>
<tr>
<td>Institution (Team leader)</td>
<td>CWRPIN (Pham Duy Trinh)</td>
<td>HUMG-GEUS (Hoang V. Hoan, HUMG)</td>
</tr>
<tr>
<td>Applied logging techniques</td>
<td>Spec. electr. resistivity (Ohm-m): SPR, R8, R16, R32, R64</td>
<td>Formation conductivity induction log, (mS/cm)</td>
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<td></td>
<td>Self potential (SP, mV)</td>
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<td></td>
<td>Natural gamma-ray Log (CPS)</td>
<td>Natural gamma-ray Log (CPS)</td>
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<td></td>
<td>Temperature (°C)</td>
<td>Temperature (°C)</td>
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</tbody>
</table>
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16 inches (406 mm, R16), 32 inches (812 mm, R32) and 64 inches (1626 mm, R64) above current electrode A. The R16 configuration is widely called short normal with relatively shallow penetration depth of the formation but relatively good depth resolution. Contrarily, the R64 long normal configuration has good penetration depth due to the wide electrode spacing but poor depth resolution. Short normal configurations are best used in moderately narrow boreholes and contrarily long normal configurations in wide diameter boreholes (MISSTEAR et al. 2007).

3.1.3.2 Self Potential (SP)

The self potential (SP) log passively measures natural potential differences at contacts of different types of geologic materials. While basically it is a result of differences in drilling fluid and the pore water, but more precisely the origin of self potential is complex and generally allows only qualitative results. It is widely used to distinguish high porous / permeable formations from low porous strata.

In groundwater exploration studies, the difference of self potential of fresh pore water and drilling fluid can be very low. On the other hand self potential measurements can help to identify high saline pore water and under ideal conditions to estimate the resistivity of the pore fluid (HATZSCH 1994).

3.1.3.3 Induction Log

An oscillating high-frequency magnetic field from a transmitter coil in the probe induces an alternating electrical current within the surrounding formation proportional to its electrical conductivity. This current, in turn, induces voltages within the receiver coils. These voltages are proportional to the formation conductivity. The formation conductivity is a function of solid phase conductivity and porewater conductivity.

Induction logging can be performed even in wells with PVC casing or dry wells. Given the fact that saline water has generally a much higher conductivity than that of the formation, induction logging is useful in groundwater exploration studies to discriminate between formations with saline pore waters and those with fresh pore waters. Qualitatively and quantitatively induction logging data are presented in chapter 4.3.2.

3.1.3.4 Natural Gamma Log

The passive (natural) gamma log measures the gamma (γ) radiation emitted from radionuclides in the mineral phases of the strata. Most commonly, such nuclides are potassium-40 (40K) as well as the isotopes from the uranium and thorium decay chain. Of these, 40K together non-radioactive potassium occurs in most clay minerals, alkali feldspars, micas, glauconite and sylvite. Gamma radiation is usually a good indicator of the clay content in sedimentary strata, although it may also indicate other lithologies such as arkoses as well as glauconite and mica rich beds.

MISSTEAR et al. 2007 summarizes some major factors which are relevant for a correct gamma log interpretation:
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- The intensity of $\gamma$-radiation count depends on the distance of the emitting beds and weakens with increasing on well diameter, this can be corrected using a caliper log.
- $\gamma$-radiation is attenuated by water and therefore increases simply after emerging from water level into air.
- $\gamma$-radiation is generated by $^{40}$K in the clay content of bentonite grouts originated from a bentonite mud.
- Some sands or sandstones may be rich in K-containing minerals (mica, feldspar, glauconite), conversely some clays may be relatively poor in potassium.

3.2 Geohydraulic Methods

Recording of geohydraulic heads and performing geohydraulic tests are crucial methods to characterize the aquifers in terms of hydraulic conductivity, transmissivity and storage capacity. In frame of this project, all monitoring wells have been equipped with automatic datalogger systems. Furthermore, step pumping test and constant rate pumping test, as well as a slug test campaign were planned. The slug test campaign was carried out in May 2010 in new monitoring wells as well as the existing national monitoring wells in Nam Dinh province and adjacent areas. Step pumping test and constant rate pumping test were scheduled in both stations Q223 and Q227. Unfortunately, unsolved land ownership and demands for water extraction licensing prevented the realization within the 1st project phase. Nevertheless, the applied methods described below represent an attempt to derive the aquifer parameters which are relevant for groundwater resources assessment.

3.2.1 Groundwater Monitoring

All monitoring wells which have proven to be hydraulically connected to the respective aquifer have been equipped with DIVER (Eijkelkamp/Schlumberger) transducer, in order to automatically monitor groundwater head, temperature and in selected wells electric conductivity. MiniDIVER, CeraDIVER or CTD-DIVER with a measuring range of 10, 20 and 50 m have been installed in each well depending on the purpose as well as the expected drawdown and salinity. The DIVER measures the absolute pressure of the water column as well as atmospheric pressure above the diver. A compensation of atmospheric pressure fluctuations have been done based on two BaroDIVER installed at the stations Q223 and Q227. All DIVER systems have been set to take hourly measurements at every full hour. Details about the installation scheme of DIVER datalogger in the monitoring wells can be found in Annex 3. Before automatic measurements started from September 2010, groundwater levels have been recorded manually each week during the period Mai to August 2011.

3.2.2 Slug Test Procedure

Slug-tests are a quick and easy possibility to estimate aquifer parameters. However, common errors while performing slug tests need to be considered, especially when
performing slug tests in monitoring wells (which are generally not designed for estimating aquifer properties). This subchapter contains general considerations about the applicability of slug tests and a brief description of the applied slug test procedure. A more detailed picture of the applied procedure is described in CWRPI 2010.

**General Remarks:** Similar to all pumping tests slug tests are only determine aquifer properties if the cavities of screen and the packing material have a larger smaller diameter than the effective pore size of the aquifer. Slug-testing analysis procedures require, that the length and diameter of the screen, the distribution of packing material and the moment in time of maximum water displacement is known. Any problems during drilling and well completion need to be reported. If there are any, it may be more appropriate not to perform the test at that monitoring well.

**Field procedure:** Slug test device have been designed by local manufacturers. The device consists of 4 pieces of steel pipe, each 1 meter length with screw connection at the connection ends to avoid the infiltration of water. Diameter (60 mm / 48 mm) and length of the device has been chosen based on the well design and applicability in field. Top and bottom of the slug are sealed and the top is connected to a steel wire. For automatic water pressure measurements, MiniDIVER transducer from Schlumberger Water Service © (SWS) were implemented, the data have been recorded on a field netbook using DIVER-Office software. It is recommended to place the transducer close to the static water surface in the well to minimize alteration of the pressure signal with depth (BUTLER et al. 2003).

The slug tests have been performed using both rising-head (quickly lower slug below groundwater level) and falling head tests (quickly lift slug out of water column). Generally, the rising-head test is preferred because “splash” effects may disturb water level measurements (WEIGHT 2008). However, especially in case of short test duration in high permeable aquifers, rising-head tests might be more feasible. The brief procedure for a rising-head test applied in Nam Dinh can be separated in the following steps:

1. **BEFORE** performing slug test: Collection of general information about the well (well design, total depth, location of screen, static water level, well completion). Are any difficulties during well construction / development reported?

2. According to step (1.) selection of the data logger parameters and suitable slug size.

3. Taking static water-level measurement – repetition is necessary to assure that no trend currently occurs. Selection of proper cable length of the slug.

Figure 8: Performing slug test - lowering of slug into monitoring well at site Q220.
4. Selection of appropriate transducer depth, about 3-5 meters below the maximum slug depth. Fixing of cable with tape to avoid movement of transducer.

5. Connection of transducer data logger to steering notebook, establishing recording parameters for starting the test. In most cases one automatic water level measurement each second was selected. Fixing of slug with cable and other security requirements to assure that slug will not be lost in well.

6. Setting of reference level for lowering the slug. Lowering of slug below water level and hold until water level equilibrates.

7. Retrieving the slug quickly! Regular manual measurements (each 15 to 30s) of the water level assure not to continue with the next test until the water level is fully equilibrated.

This process should be repeated to make sure that the data behave similarly and to identify any errors.

Analyzing slug test data: According to the specific conditions of the each tested well/aquifer the appropriate analytical method need to be selected in order to calculate reliable hydraulic parameter from slug test data. The procedure of analysis and interpretation of slug test data was supported by the application of the software AQTESOLV Pro 4.5 (HydroSOLVE Inc.). Hereafter, the analytical models applied in frame of this study are briefly described, according to BATU 1998; FETTER 2001 and DUFFIELD 2007:

- HVORSLEV 1951 provides a simple method used for confined and unconfined aquifers. The methods has been proven to provide more accurate results in case of but fully penetrating screens.

- BOUWER AND RICE 1976, designed a method for slug test analysis in partially or fully penetrating wells in unconfined aquifers. According to FETTER 2001, this method can be used also in confined aquifers if the well screen is located significantly below the confining layer.

- Slug test analysis according to VAN DER KAMP 1976 is recommended to apply for aquifers with high conductivity, showing oscillatory response which his called in this study the “underdamped case” (FETTER 2001). This method requires an estimation of storativity, therefore, this approach has been neglected in this study facing the lack of reliable pumping test data.

- BUTLER 1998 extended the HVORSLEV 1951 solution for a single-well slug test in a homogeneous, anisotropic confined aquifer in order to include inertial effects in the test well. The solution accounts for oscillatory water-level response (“underdamped case”) sometimes observed in aquifers of high hydraulic conductivity. BUTLER 2002 modified the method to incorporate frictional well loss in small-diameter wells.

In frame of this study, damped (“normal”) slug test results from Nam Dinh have been interpreted according to Bouwer and Rice, given the fact that the well screen is always well below the confining layer. Calculations according to Hvorslev were carried out for cross-checking reasons only and confirmed the Bower and Rice values. In case of the underdamped, oscillatory, response of high permeable aquifer (e.g., Q227) slug test data
have been interpreted following BUTLER 1998. The results are documented in Annex 7, interpretation in chapter 4.2.1.1.

### 3.2.3 Calculating Hydraulic Parameter using Barometric Efficiency

Barometric pressure fluctuations can cause significant effects on the water level in a well tapping a confined aquifer. The model of JACOB 1940 (in BATU 1998) assumes that the barometric pressure change is transmitted without attenuation to the interface between the confining layer and the confined aquifer. According to the theory of JACOB 1940, the fluctuations in a well in a confined aquifer are directly depending on the elasticity of the aquifer, which is a function of the compressibility of the water and the skeleton of the aquifer.

The barometric efficiency (BE) is defined as the ratio of change in hydraulic head to the change in barometric pressure head. BE can be used for the correction of drawdown data in long-term pumping tests. Moreover, BE can be used to estimate the storage coefficient of a confined aquifer based on the confined aquifers response to barometric fluctuations. Due to lacking pumping test data in Nam Dinh, the BE has been determined in this study in order to calculate the storage coefficient. The brief summary of the barometric efficiency concept below is following JACOB 1940 and HANTUSH 1964 (in BATU 1998).

As mentioned above, the barometric efficiency (BE) is defined as the ratio of change in hydraulic head $\Delta h$ (m) to the change in barometric pressure head. The barometric pressure head (m) is defined by the atmospheric pressure ($p_a$) and the specific weight of water ($\gamma$):

$$BE = \frac{\Delta h}{\Delta \left( \frac{p_a}{\gamma} \right)}$$

Figure 9: Time series of groundwater head versus barometric pressure fluctuation (both in m H$_2$O, interval 1 hour) for December 2011 in Q221b clearly documents their inverse correlation, so that decreasing groundwater heads are a response to increasing air pressure and vice versa.
With the assumption that the whole atmospheric pressure head change is transmitted to the aquifer without any reduction and aquifer grains are assumed to be incompressible, the application of the elasticity and compressibility as well as specific storage concept yields to the following relationship (BATU 1998):

$$S = \frac{\gamma n \beta b}{BE}$$

(2)

As a consequence, the storage coefficient (S) of a confined aquifer can be derived in case the BE, the thickness of aquifer (b), the specific weight of water (γ), the porosity (n) of the aquifer and the compressibility of water (β) is known. Assuming an average groundwater temperature of 25°C, γ = 9.777 (kN/m³) and β = 4.5 x 10⁻¹⁰ (m²/N) have been used for further calculations (BATU 1998).

Figure 9 shows the inverse correlation between barometric pressure and groundwater heads at the example Q221b. In this study, BE has been estimated as an average of two data sets for different days for all wells in confined aquifers, following the method developed by CLARK 1967 (in BATU 1998 and SPANE 1999).

Clark’s method suggest to determine the BE from the slope of a summation plot of the incremental changes in the downhole formation pressure, versus the incremental change in atmospheric pressure. A preliminary data processing step results into a more robust estimation of BE using the Clark’s method in confined aquifer wells that are influenced by other pressure trends, e.g., distant ground water withdrawals.

The Clark method employs observed changes in barometric pressure head (∆(p/γ)) and hydraulic head (∆h) for constant time increments to estimate the barometric efficiency. Clark’s method assigns a positive sign to ∆(p/γ) when the barometric pressure is decreasing. To estimate the barometric efficiency, two sums are made: Σ∆(p/γ) and Σ∆h, in accordance with the following rules (CLARK 1967, in BATU 1998):

Figure 10, left: Time series of groundwater head versus barometric pressure fluctuation on 10th April 2011 in Q221b (both in m H₂O). Right: Estimating barometric efficiency based on measured-head data from Q221b on 10th April 2011.
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1. when $\Delta(p_{w}/\gamma)$ is zero, neglect the corresponding value of $\Delta h$ in determining $\sum \Delta h$,

2. when $\Delta h$ and $\Delta(p_{w}/\gamma)$ have the same signs, add the absolute value of $\Delta h$ in determining $\sum \Delta h$,

3. when $\Delta h$ and $\Delta(p_{w}/\gamma)$ have opposite signs, subtract the absolute value of $\Delta h$ for determination of $\sum \Delta h$.

Then, $\sum \Delta(p_{w}/\gamma)$ is the sum of the absolute values of $\Delta(p_{w}/\gamma)$. Once these rules are used for generation of the summated values of $\sum \Delta h$ and $\sum \Delta(p_{w}/\gamma)$, the barometric efficiency is estimated from the following equation:

$$BE = \frac{\sum \Delta h}{\sum \Delta(p_{w}/\gamma)}$$  \hspace{1cm} (3)

Measures of $\Delta h$ are plotted on the $y$-axis, and those $\Delta(p_{w}/\gamma)$ are plotted on the $x$-axis. A line is fitted to the plotted points (Figure 10). The slope of the fitted line is the estimate of barometric efficiency (BE) (GÉRARD 2007). It must be noted that “Clark’s” method, assume a constant BE, despite of the fact that the hydraulic system may lead to differences of short-term BE and long-term BE (SPANE 1999).

3.2.4 Calculating Hydraulic Parameter using Tidal Effects

In coastal areas the periodic rise and fall of water level in the adjacent ocean, lake or hydraulically connected stream can produce sinusoidal groundwater level fluctuations in the adjacent aquifers. Also hydraulic heads of confined aquifers which are separated from the surface water body by an extensive confining layer are responding to tidal effects due to changing load on the aquifer (BATU 1998).

Sea water level and coastal Red River water level data were available for December 2010. Within that time span, tidal high and low stand have been found to have an average period of about 24.8 hours. Tidal amplitudes vary periodically at the Red River mouth within 1 to 3 m,

![Figure 11: Tidal water level fluctuation at the Red River mouth (Ba Lat station) and open sea (Hon Dau station) in December 2010. Note that apparent high average sea level +2 m asl is caused by different national reference benchmarks in Vietnam.](image)
as documented at Ba Lat station (Red River mouth) and Hon Dau station (Hon Dau island) in December 2010 (see Figure 11). Please note the apparent high average sea level data in Hon Dau station (+2 m asl) are caused by two different national reference systems in Vietnam.

Figure 11 clearly shows the tidal influence in the groundwater fluctuation of deeper confined aquifers in the example of Q225b and Q226a. Similar behaviour has been observed in other wells close to the open sea or large rivers underlying tidal fluctuations. Considering tidal fluctuations as a continuous natural pumping test, an analytical solution is required to translate the observed response of groundwater levels into the geohydraulic parameter of an aquifer.

A simplified model of tide-induced groundwater flow is described in the solution by JACOB (1950), considering a vertical beach, a straight coastline and one-dimensional flow in a coastal confined aquifer (Figure 13). Jacob’s solution is also applicable as an approximation to water table fluctuations of an unconfined aquifer if the fluctuation range is small in comparison to the saturated aquifer thickness (FETTER 2001).
The solution indicates that the amplitude of the tide-induced groundwater head fluctuation decreases exponentially with the distance from the coast, whereas the time lag increases linearly with the distance. The attenuation speed decreases with the diffusivity of the aquifer (the ratio of transmissivity to storage coefficient) and increases with the angular velocity of the sinusoidal sea tide. The governing flow equation in one dimension is according to JACOB 1950 (in SMITH 1994):

$$h_x = h_0 e^{-\frac{\sqrt{\pi S}}{t_0 T}} \sin \left( \frac{2\pi t}{t_0} - x \frac{\pi S}{t_0 T} \right)$$

Where $h_x =$ groundwater level (m), $x =$ distance from surface water body (m), $t =$ time (day), $t_0 =$ period of tidal oscillation (day), $h_0 =$ amplitude of tide (m), $T =$ transmissivity of aquifer ($m^2$/day), $S =$ storage coefficient (=storativity) of aquifer. Based on this solution, JACOB 1950 provides two methods for the analysis of an observed tidal groundwater level fluctuation, the amplitude attenuation method and the time lag method.

The **time lag method** was used by FERRIS 1951 to estimate the diffusivity of an aquifer beside a tidal river using the intervals between the tidal maxima measured in the monitoring wells (HALBERT et al. 1996). The solution shows that the fluctuation in water levels remains cyclic with a time lag and a decrease in intensity with distance from the river. The equation for the time lag method according to SMITH 1994 is:

$$\text{timelag} = x \sqrt{\frac{t_0 S}{4\pi T}}$$

The time lag [day] can be derived from the graphic analysis of groundwater level fluctuation versus ocean tide and the aquifer storativity can be calculated using the formula above:

$$S = \frac{4\pi T (\text{timelag})^2}{x^2 t_0}$$

The **diffusivity method** assumes one-dimensional flow in a confined aquifer which directly abuts a tidal body of water, the amplitude of water table oscillation in the confined aquifer at distance $x$ ($h_x$) from the river bank or sea shore is given by (SMITH 1994):

$$h_x = h_0 e^{-\frac{\sqrt{\pi S}}{t_0 T}}$$

If the amplitude of the tide $h_0$ and the amplitude of the groundwater level fluctuation ($h_x$) at a distance $x$ from surface water body are known from field measurements (Figure), it is possible to calculate the diffusivity $D$ by rearranging the previous equation and, therefore, when local transmissivity is known also the storage coefficient of the aquifer (CAROL et al. 2009):
Jacob’s solution provides two methods calculating aquifers diffusivity from its tidal response using a relatively simple analytical model. It has been frequently applied previously and inconsistencies have been observed in some case studies. The reason is probably within the assumed model, based on the simple assumptions of the aquifer configurations such as a single, horizontal, and landward infinitely extending aquifer, vertical beach and straight coastline. Therefore, the leakage of the semi-permeable layers, irregular boundary shape, and definite aquifer geometry are not considered (Li et al. 2003). The results as well as their applicability in frame of this study are presented and discussed further in chapter 4.2.1.2.

3.3 Sediment Sampling & Analysis

Sediment samples have been collected from the screen depths of all wells as well as other selected strata. About 1 kg of representative sample, depending on availability of the material, has been collected for analysing grain size as well as mica content and have been kept as retain samples.

For grain size analysis, the most suitable laboratory in Hanoi was found in the Road Laboratory of the Institute of Transport Science and Technology (ITST). Grain size analysis and analysis of the mica content has been carried out for a total of 33 sediment samples including filter material of all installed monitoring wells and representative samples from other strata. Particle size analysis has been performed according to USA standard AASHTO T27 which has been adopted as Vietnamese standard TCVN 7572-06. However, the method was generally designed for the construction sector and, therefore, it has shortcomings in the fine fraction. The smallest sieve size is 0.075 mm (75 µm), resulting in the incapability to distinguish between the finest sand, silt (2 µm-63 µm) and clay fraction (<2 µm).

Although it would be more precise to characterize directly the diameters of cavities rather than those of the grains, the collection of undisturbed sediment samples as needed for advanced laboratory techniques such as He- or Hg-porosimetry was not possible. Therefore, total porosity and hydraulic properties has been estimated in this study based on the grain size distribution. The applied procedure is briefly described below, following ODONG 2007; SONG et al. 2009; VUKOVIC et al. 1992.

According to VUKOVIC et al. 1992, total porosity \( n \) may be derived from the empirical relationship with the coefficient of grain uniformity \( \mu \) as follows:

\[
n = 0.255 \left( 1 + 0.83^\mu \right)
\]  

where \( \mu \) is the coefficient of grain uniformity and is given by:
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The parameter \( d_{60} \) and \( d_{10} \) in the formula represent the maximal grain diameter (mm) of the finest 60% and 10% of the sample. Hydraulic conductivity (K) can be estimated by particle size analysis of the sediment of interest, using empirical equations relating K to some physical properties of the sediment (VUKOVIC et al. 1992):

\[
K = \frac{g}{v} C \cdot f(n) d_e^2
\]  

where \( K \) = hydraulic conductivity; \( g \) = acceleration due to gravity; \( v \) = kinematic viscosity ; \( C \) = sorting coefficient; \( f(n) \) = porosity function, and \( d_e \) = effective grain diameter. The kinematic viscosity \( (v) \) is related to dynamic viscosity \( (\mu) \) and the fluid (water) density \( (\rho) \) as follows:

\[
v = \frac{\mu}{\rho}
\]  

Earlier studies have presented various formulae derived from the equation (11) but with varying sorting coefficient \( (C) \), porosity function \( (f(n)) \) and effective grain diameter \( (d_e) \) values and their domains of applicability (ODONG 2007; SONG et al. 2009). In this study the different methods have been selected in terms of its applicability and the reasonability of the result:

HAZEN:

\[
K = \frac{g}{v} \cdot 6 \cdot 10^{-4} \left[ 1 + 10 \left( n - 0.26 \right) \right] d_{10}^2
\]  

HAZEN 1892 formula was originally developed for determination of hydraulic conductivity of uniformly graded sand but is also useful for fine sand to gravel range, provided the sediment has a uniformity coefficient less than 5 and effective grain size between 0.1 and 3mm. This formula is based on \( d_{10} \) value only and, thus, is less accurate than Kozeny-Carman equation.

KOZENY:

\[
K = \frac{g}{v} \cdot 83 \left[ \frac{n^3}{(1-n)^2} \right] d_e^2
\]

And:

\[
\frac{1}{d_e} = \sum_{i=1}^{j-1} (f_{i+1} - f_i) \cdot \frac{d_{i+1} + d_i}{2 \cdot d_{i+1} \cdot d_i}
\]

This equation divides grain size distribution into a number of fractions to assess the effective diameter \( d_e \). Thus, further parameter implemented, such as the number of fractions \( (j) \), fraction number \( (i) \), Fraction \( i \) of sample \( (f_i) \) and diameter of fraction \( i \). The Kozeny equation is widely accepted, using derivations of permeability as a function of the porosity, particle size distribution, the particle shape, and the void ratio of the medium. This equation was originally proposed KOZENY 1927 and then modified in KOZENY 1953 (CRONICAN et al. 2004). It is not appropriate for soil or sediments with effective size above 3 mm or for clayey sediments (CARRIER 2003).
3. General Approach & Applied Methods

Beyer:

\[ K = \frac{g}{v} \cdot 6 \cdot 10^{-4} \log \frac{500}{U} d_{10}^{-2} \]  \hspace{1cm} (16)

This method does not consider porosity and therefore, porosity function takes on value 1. Beyer (1964) formula is often considered most useful for materials with heterogeneous distributions and poorly sorted grains with uniformity coefficient between 1 and 20, and effective grain size between 0.06 mm and 0.6 mm (Odong 2007).

Slichter:

\[ K = \frac{g}{v} \cdot 1 \cdot 10^{-2} n^{1.287} d_{10}^{-2} \]  \hspace{1cm} (17)

The Slichter formula (Slichter 1899) is most applicable for coarse grained material with grain size between 0.01 and 5 mm (Odong 2007).

Please note that the porosity calculation above (9) refer to the total porosity volume of a sampled formation. For hydrogeological studies the effective porosity \( n_e \) is more relevant. \( n_e \) is the portion of the total pore space which exists of interconnected pore spaces and is capable of releasing its contained water. Advective groundwater flow occurs only in the \( n_e \) portion. It can be calculated, e.g., from the specific discharge of a well divided by the mean velocity of conservative tracer. Since such data are not available, a rough estimation for high conductivity aquifers is possible using of the empirical Marot relationship (Marotz 1968):

\[ n_e = 0.462 + 0.045 \cdot \ln(K) \]  \hspace{1cm} (18)

This logarithmic correlation is only valid for high conductive aquifers with a minimum \( K \) of \( \sim 10^{-5} \) m/s (Kollmann 1986).

3.4 Groundwater Sampling & Analysis

In Mai 2010 one field campaign was carried out to collect water samples from the constructed monitoring stations Q220 – Q229, as well as the existing groundwater monitoring stations Q92, Q108 - Q111 and surface water. In order to compare water chemistry during dry and rainy season, a second sampling campaign was scheduled in November 2010. Unfortunately, this sampling campaign was not realized due to an unforeseen lack of funding at the end of the 1st project phase.

Before collecting the groundwater sample, minimum 2-3 volumes of the water column in each well has been pumped using a submersible pump (Grundfos MP1). Field parameters, such as specific electric conductivity (EC), pH, dissolved oxygen (DO), and temperature were monitored on-site using probes from WTW 340i multiparameter test kit. Electrodes were calibrated regularly to maintain stability, following the procedures outlined in WTW manual. Groundwater samples were taken for analysis when field parameters stabilised, to ensure representativeness of groundwater samples. A sampling protocol was designed in both Vietnamese and English language and used to collect the field data about sampling location and procedure. The English version of the field protocol is documented in Annex 4.
3. General Approach & Applied Methods

Bicarbonate (HCO$_3$) was determined by titration of 5 mL sample with hydrochloric acid (HCl) down to an endpoint of pH 4.3. Titration down to pH 8.2 was not necessary because pH range of all samples lies within pH 4.3 – 8.2. The titration was performed with an Alkalinity Test from Merck® (111109) using the colour indicators (pH 4.3: bromocrescol green - methyl red, pH 8.2: phenolphthalein).

Sampling bottles and syringe were rinsed with the referring water sample before sampling. At each location, five sampling bottles have been collected following the procedures below:

- **Cations**: Major/ minor cations and trace elements. Filtrate with syringe and one-way syringe filter (0.4 µm) and fill 100 mL HD-PE bottle. Sample preservation: acidification with 1 mL concentrated nitric acid (HNO$_3$, p.a.).

- **Anions**: 1x500 mL PE-bottle, fill as bubble-free as possible, no filtration and preservation of sample. In case of high content of organic substances (high DOC, algae etc.) nutrients should analyzed in-situ or sample should be “poisoned” before transport in order to prevent microbial activities.

- **Stable H$_2$O-isotopes ($^2$H, $^{18}$O)**: Filtrate with syringe and filter, fill 100 mL HDPE-bottle as bubble-free as possible.

- **Tritium**: At preselected sampling sites, fill 1 Liter HDPE-Bottle.

- **$^{14}$Carbon**: At preselected sampling sites, specific sampling has been applied to determine $^{14}$C content of dissolved inorganic carbon. A specific content of Carbon was precipitated in form of BaCO$_3$, after determination of the site specific carbonate content (mainly HCO$_3$) in mg/L using a commercial Alkalinity test (see in-situ parameters). The sampling procedure has been applied by staff from INST-VAEC.

- Additionally: For quality check of the used HNO$_3$ acid (p.a.) as well as analytical procedures, two blank samples have been collected. One 100 mL bottle with distilled H$_2$O and 1mL HNO$_3$ccsp, and another 100 mL bottle with distilled water only have been sent to VAST and BGR laboratories to determine anions and cations.

Two sets of samples have been collected for anion, cations and trace elements. One set has been analyzed in the water laboratory of the BGR, another set in IET-VAST, Hanoi (Institute of Environmental Technology, Vietnam Academy of Science and Technology). Analyzes of the isotopic parameters have been carried out in the INST-VAEC (Institute for Nuclear Science and Technology, Vietnam Nuclear Environmental Agency).

Data reliability checks have been carried out to identify unreliable from the analyzed data sets. The electroneutrality test is based on the physical fact that the sum of positive and sum of negative

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Laboratory</th>
<th>Analytical Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cations</td>
<td>VAST, Hanoi</td>
<td>IC, AAS</td>
</tr>
<tr>
<td></td>
<td>BGR, Hannover</td>
<td>IC, AAS, ICP-OES</td>
</tr>
<tr>
<td>Anion</td>
<td>VAST, Hanoi</td>
<td>IC, AAS</td>
</tr>
<tr>
<td></td>
<td>BGR, Hannover</td>
<td>IC, AAS, ICP-OES</td>
</tr>
<tr>
<td>Trace elements</td>
<td>VAST, Hanoi</td>
<td>ICP-MS</td>
</tr>
<tr>
<td></td>
<td>BGR, Hannover</td>
<td>ICP-OES, ICP-MS</td>
</tr>
<tr>
<td>$^2$H, $^{18}$O</td>
<td>VNEST, Hanoi</td>
<td>EA-MS</td>
</tr>
<tr>
<td>Tritium</td>
<td>VNEST, Hanoi</td>
<td>LSC</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>VNEST, Hanoi</td>
<td>LSC</td>
</tr>
</tbody>
</table>

Table 2: List of analytical instruments applied for analysing the collected water samples.
charges of dissolved ions in any water must be equal. All major (>1 g/L) anions and cations transformed into molequivalent per Volume have been used for this test. The deviation percent of anions and cations should be <5 %, but is considered to be still acceptable if <10 %. Generally, the percent error of analysis from BGR was within ±2 %. With this method, some outliers in the VAST data set have been identified and corrected (tying error, order of magnitude) resulting in a percent error generally <10 %. Quality control of trace constituents and isotopes is more difficult. This has been done using a statistical approach focusing the expected range and distribution of each parameter.
4 Integrating Results into a Conceptual Model

4.1 Geology of Nam Dinh

This chapter presents the geological background and, therefore, fundament for the conceptual hydrogeological understanding of the Nam Dinh area. This comprises a brief characterization of the major structural features in the working area, followed by an outline of paleo-sea level fluctuation during younger quaternary time and its significant role for the development of the recent RRD (chapter 4.1.1). This provides the background for the stratigraphic classification and characterization of the geological strata (chapter 4.1.3).

4.1.1 Paleo-Sea Level Change and Quaternary Geology

The geologic and geomorphologic development of the RRD was controlled by the glacieustatic sea-level change and the ongoing tectonic subsidence of the Red River Basin. Continuous accumulation of the sediment load has been interrupted by repetitive erosion events during the glacial periods due to the associated sea-level declination in the late Pleistocene and Holocene. Especially the last glacial event hugely influenced both, distribution and interconnection of groundwater bearing strata in the subsurface of the RRD as well as the salinity of pore waters.

During the last interglacials sea-level high stand about 125,000 years BP, extended coastal areas of today’s RRD has been flooded. Hence, the area was exposed to intrusion of seawater probably resulting in the regional salinization of pore water within permeable Pleistocene and underlying sediments. Subsequently, the last glacial period began about 120,000 years BP. It was accompanied by a general trend of sea-level declination of several tens of meters and interrupted by temporary transgression events (Figure 14). Sea-level declination implies a deeper discharging system, increasing the relief and the erosion energy of the receiving Red River and its tributaries.

During the maximum sea-level low stand up to 125 to 133 m asl (HANEBUTH et al. 2009), erosion of earlier Pleistocene sediments culminated in the

![Figure 14: Sea level fluctuation relative to modern sea-level (m MSL) during the last 200,000 years, reconstructed from the Pacific δ18O record (redrawn and modified after WAELBROECK et al. 2002). Maximum low stand during last glacial was about -133 to -125 m (HANEBUTH et al. 2009).](image-url)
incision of deep river valleys. As consequence, in comparison to modern times a much steeper hydraulic gradient, between a recharge areas in the inland and the ocean has been

Figure 15: Paleographic maps illustrating the Holocene evolution of the Red River (Song Hong) Delta (cal. Kyr BP = calibrated $^{14}$C age (x1000 years) before present, TANABE et al. 2003b). Please note: groundwater table contours are derived from depth of groundwater bearing strata and therefore representing the Pleistocene-Holocene sediment boundary rather than hydraulic groundwater heads.

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developed. The location of the Red River (Song Hog) valley was initially described by Tanabe et al. 2003b; Tanabe et al. 2006 derived from archive drilling data (Figure 14). During the transgression starting from 19000 to 20000 years BP, the paleo-river valleys have been rapidly filled with estuarine, tidal, and fluvial sediments (Xue et al. 2010). Accumulation peaked from 13000 to 9500 years BP when sea-level rose rather constantly with approx. 10 mm/a, as described for the Mekong Delta (Tjallingii et al. 2010).

Sea level rise decelerated 9000 – 6000 years BP when the valley was almost filled (Tanabe Tanabe et al. 2006). Especially the coastal areas of the RRD, such as Nam Dinh, were covered by sea water during extended periods of the early and middle Holocene resulting in fine grained marine sediments with saline pore waters (Figure 15).

Tanabe et al. (2006) estimates a relatively stable local sea-level at +2-3 m above the present sea level between 6000 – 4000 years BP. While regression of the sea to modern levels, accumulation expired in the late Holocene with fine grained, low permeable flood sediments and peat layers come apart from the active river channels.

Overall, the cycle of erosion and sedimentation described above occurred several times during the repeated transitions of glacial and interglacial periods. This leads to a quite complex architecture of Pleistocene and Holocene strata in Nam Dinh province area dominated by extensive alluvial sediments, incision of the paleo-Red River (Song Hong) channel and marine sedimentation during the recent Holocene time.

### 4.1.2 Geological 2D-Structure

As mentioned in chapter 2, the tectonic features of the Red River basin are a major driver for the development of the RRD. Therefore, especially in close vicinity to the adjacent Mesozoic bedrocks, tectonic structures and features are quite complex. This is also the case for Nam Dinh province which is indicated in the sketch map in Figure 16. Nam Dinh lies above the Ailao Shan–Red River shear zone within the Song Chay and Song Hong fault. Previous tectonic studies characterize these major faults as normal fault with dipping 72° NE (Nguyen Van Cu et al. 1996), international reports characterize them as strike-slip faults with left-lateral shearing (Searle 2006). Further minor parallel faults displace the Mesozoic hard rocks. One major structural feature in the subsurface of the Nam Dinh province is the uplifted Vu Ban block (Nguyen Van Cu et al. 1996), indicated by few Proterozoic outcrops in the Northwest of the province. For the conceptual understanding, the location of major and minor fault zones has been adopted from the Geological Map 1:200 000 (Nguyen Thanh Van et al. 2005). Another important structural feature is the incision of the paleo Song Hong (Red River) valley, which is, according to Tanabe et al. (2003), surrounding the Vu Ban Block and crossing Nam Dinh province to the sea (Figure 16).
Based on the information described above and IGPVN drillings as well as selected achieve drillings, 5 cross sections have been drawn to provide a clearer picture of the 2D-Geological Structure (Figure 18, location see Figure 17). This provides insight into local and regional hydraulic connections and therefore groundwater flow and transport path of solutes within the hydrogeological units. Holocene strata have been summarized in the cross sections to Q1, whereas the older geologic units also represent hydrogeological units (see next section). Please note that some structural features as well the basis of Neogene sediments need to be assumed (“?”) due to lacking data.

A further 3D-perspective on the tectonic and geologic structures in the Nam Dinh area is provided in frame of the 3D-structural modelling (see this report, Part B).
Figure 18: Geological Profiles 1-5 (Location see Figure 17), mainly based on the Geological mapping 1:200 000 and drilling logs for the National as well as IGPVN Monitoring wells (40x super elevation). Topography is following the digital elevation model derived from ASTER satellite data. Red lines are representing faults; nomenclature for geological units is following Table 3.
4. Integrating Results into a Conceptual Model

4.1.3 Characterisation of Geological Units

As demonstrated above, the subsurface structure and, thus, the hydrogeology setting of the Red River Delta is somewhat complex. Especially in the coastal and in vicinity to the adjacent bedrocks such as it is the case in Nam Dinh area, active faulting and repetitive transgression and regression events have resulted in a heterogeneous structure of intersecting aquifers and aquicludes. Geologic formations in that area with relevance for groundwater supply last from Triassic bedrocks and late Neogene (Pliocene) semiconsolidated sediments up to unconsolidated sediments of Pleistocene and Holocene time. Table 3 presents a stratigraphic overview based on the geological mapping by the Department of Geology (NGUYEN VAN CU et al. 1996) updated regarding the recent nomenclature in Vietnam (MINISTRY OF INDUSTRY 2001; TRAN TAT THANG et al. 2000) and international publications (TANABE et al. 2003b; TANABE et al. 2006). Note that, associated hydrogeologic units consequently comprise high permeable (aquifer) and low permeable (aquiclude) layers.

The following subchapter describes the sedimentary formations encountered in the Nam Dinh province starting from the oldest up to the most recent, mainly based on the lithological

Table 3: Stratigraphy and Hydrostratigraphy of the strata in the Nam Dinh area. Associated base ages according to NGUYEN VAN DAN 2009; TANABE et al. 2003b; TRAN TAT THANG et al. 2000 and IUGS-ICS (GIBBARD et al. 2010).

<table>
<thead>
<tr>
<th>Era</th>
<th>System</th>
<th>Series</th>
<th>Sub-series</th>
<th>Geologic unit</th>
<th>Formation</th>
<th>Facies type*</th>
<th>Hydro-strat.</th>
<th>Base Age (Mio a BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cenozoic</td>
<td>Quatern-</td>
<td>Lower</td>
<td>Upper</td>
<td>Q₂¹ hh</td>
<td>Hai Hau, lower</td>
<td>am, mb, m</td>
<td>qh1</td>
<td>0.01**</td>
</tr>
<tr>
<td></td>
<td>ary</td>
<td></td>
<td>Middle</td>
<td>Q₂² hh</td>
<td>Hai Hau, upper</td>
<td>m</td>
<td>qh1</td>
<td>0.007**</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
<td>Q₂³ tb</td>
<td>Thai Binh m, mv, amb, am, ab, a</td>
<td>qh2</td>
<td>0.004**</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
<td>Q₁³ vp</td>
<td>Vin Phuc a, am, m</td>
<td>qp2</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Middle</td>
<td>Q₁²-³ hn</td>
<td>Ha Noi am, a</td>
<td>qp1</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower</td>
<td>Q₁¹ lc</td>
<td>Le Chi am</td>
<td>pr</td>
<td>2.58***</td>
<td></td>
</tr>
<tr>
<td>Neogene</td>
<td>Pliocene</td>
<td>N₄ vb</td>
<td>Vin Bao am (deltaic)</td>
<td>n</td>
<td>5.33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Triassic</td>
<td>T₂ dg</td>
<td>m</td>
<td>t₂</td>
<td>246</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>T₁ tl</td>
<td>m</td>
<td>t₁</td>
<td>251</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proterozoic</td>
<td></td>
<td>PR sh</td>
<td>pr</td>
<td>1800-2500</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* (a) - alluvial; (m) - marine; (b) - swamp, bog; (v) - aeolian; according to DGMS Vietnam
** Calibrated ¹⁴C ages according to Tanabe et al (2003b).
*** Quaternary base has been redefined by IUGS-ICS in 2009 to 2.58 Mio a BP, including the former upper Pliocene.
description of IGPVN well drillings and the geological mapping 1:50 000 (NGUYEN VAN CU et al. 1996).

Paleoproterozoic - Red River Complex (PR1 sh)

The Red River Complex was established and described by A.E Dovjikov in 1965. These ancient metamorphic rocks mark few elevated hills in the NW of Nam Dinh, which are scattered along a 4 km² area in NW-SE direction. Outcrops can be found in the so-called Goi, Le Xa and Ngan mountains in the Vu Ban district, as well as Phuong Nhi and An Lao mountains in Y Yen district. The mountains mark the top of the uplifted Vu Ban Complex having a structural direction of NNW-SSE and NW-SE. Strike slip and reverse faults mark the contact to the adjacent Triassic rocks to the West.

Based on previous studies and own observations at outcrops (Figure 19), the Red River Complex mainly consists of

- Gneis with bitotite, garnet and sillimanite is commonly found in the Vu Ban Block. Rock texture reaches from small to middle mineral size with spattered large idiomorphic garnet with lengths from 0.5 to 0.8 cm.

- Beside higher plagioclase contents, the Plagiogneis typically been found in Goi and Le Xa mountains contains also biotite, garnet and sillimanite minerals. The texture is characterized by small to medium mineral sizes and idiomorphic garnet.

- Phuong Nhi mountain consist of Quartz schist with feldspar, biotite and garnet. Rock texture is dominated by small pseudo-idomorphic minerals.

The Red River complex is subject of heavy folding and faulting as observed at outcrops in Nam Dinh province. In Figure 19 the existence of wet ground and shallow ponds at the base of the elevated outcrop also during dry season indicates a possibly water-bearing fault zone.

Figure 19: Outcrop of the Red River complex in 612286 E, 2248505 N (UTM, WGS84, 48N). Quartzite fracture filling along a NW-SE striking fault zone (dashed line) in metamorphic gneiss of the Vu Ban block (photo fw).
4. Integrating Results into a Conceptual Model

**Triassic - Tan Lac Formation (T₁ tl)**

The early Triassic Tan Lac formation was established by Phan Cu Tien in 1977. It is only exposed in few areas in Ha Nam and Ninh Binh province. In previous studies this formation has not been described yet to exist in the subsurface of Nam Dinh area. Nevertheless, the IGPVN drilling Q220 in Y Yen district drilled below unconsolidated sediments into fine sandstone and siltstone hard rock, which have been interpreted to belong to T₁ formation in vicinity to the Song Hong fault. Stratigraphically, this formation overlies the Vien Nam formation (Early Triassic, T₁ vn), which is not exposed in the working area. Generally, a tectonic contact to the Proterozoic basement and younger Dong Giao formation is assumed. According to TRAN TAT THANG et al. 2000, this formation is characterized by fine sandstone and siltstone, furthermore tuffaceous sandstone, lime- and marlstone. In Q220 this formation was discovered at 36 m depth. The core of this drilling can be lithologically divided in an upper part with shale and siltstone and a lower part with fine sandstone and calcareous shale.

**Triassic - Dong Giao Formation (T₂ dg)**

The Dong Giao formation was established by Jamoida and Pham Van Quang in 1965. This formation forms extensive mountain chains with a strong relief in the neighboring Ha Nam and Ninh Binh as well as in other provinces in North Central Vietnam. The formation has not been discovered in Nam Dinh by own drillings, however, archive data report its existence in the subsurface of Nam Dinh in vicinity to the border to Ha Nam province.

The Dong Giao formation is famous for dark-grey thin bedded limestone, light-grey massive limestone and dolomititic limestone which are commonly subject of extensive karst dissolution. Mapping studies from Ninh Binh province (TRAN TAT THANG et al. 2000) report a general thickness of about 400-450 m for the thin bedded limestone and about 200-250 m for the massive limestone. The karsted fissured zone is roughly estimated to extend to 100 m bgl. Its evolution is possibly associated with periods of low standing of receiving stream and sea level.

**Neogene, Pliocene - Vinh Bao Formation (N₂ vb)**

The Vinh Bao formation was established by V.K. Golovenok in 1965 based on exploration drillings at Vinh Bao town, Hải Phong Province. The Vinh Bao formation is widely present in the deeper subsurface of the Nam Dinh province, except of areas of the uplifted Vu Ban block (NGUYEN VAN CU et al. 1996) in the North-West and West. The Vinh Bao formation is not exposed on the surface, lithological characteristics and depth informations are derived from 6 IGPVN well drillings, whereas none of them have met the basis of the formation.

Top of Vin Bao formation was met from 70 m bgl (in NW of Nam Dinh) down to 151 m bgl close to the coast in the SE, maximum observed thickness is >65.0 m. Archive drillings (NGUYEN VAN CU et al. 1996) show that in the Northwest and West of Nam Dinh area, the basis is an unconformity with direct contact to the Mesozoic and Proterozoic basement (T₁, PR₁), it is not clear if this is also the case further east. The top boundary of the Vinh Bao
4. Integrating Results into a Conceptual Model

A formation is expected to be an unconformity to the covering early Pleistocene sediments of the Le Chi formation and Ha Noi formation.

Composition of Vinh Bao formation as reported from Nam Dinh area (NGUYEN VAN CU et al. 1996) is dominated by fine to medium sandstone with intercalated laminated beds of clay- and siltstone. In IGPVN drillings, the Vinh Bao formation is typically represented by semiconsolidated siltstone and fine sandstone intercalated with fine to coarse unconsolidated sand. The Vinh Bao formation is believed to be deposited in a deltaic-neritic environment (NGUYEN VAN CU et al. 1996).

**Quaternary, Lower Pleistocene – Le Chi Formation (Q, lc)**

The Le Chi formation was established by Ngo Quang Toan in 1987 based drilling data at Le Chi commune, Gia Lam District, Ha Noi. Le Chi formation was identified in 3 monitoring stations at a depth range within 93 to 118 m bgl. The maximum thickness is 18 m in borehole Q222 and the minimum about 4 m in Q223. Le Chi formation has an unconformity to the underlying Vinh Bao formation and to the upper-middle Pleistocene sediments of the Ha Noi formation.

Based on the IGPVN monitoring drillings, the Le Chi formation mainly consists of coarse grained material such as gravel and medium to coarse sand. Sporadically, beds of greyish silt are intercalated. According to NGUYEN VAN CU et al. 1996, the sediments have been deposited in an alluvial to marine environment.

**Quaternary, Upper-Middle Pleistocene – Ha Noi Formation**

The Ha Noi formation was established by Hoang Ngoc Ky in 1973. There are no outcrops of this formation in Nam Dinh area but it was identified in almost all IGPVN drillings. Depth of the top of the formation is increasing from northwest (62 m bgl) to the SE coastal area (96 m bgl). Average thickness is about 24 m with a maximum at 49 m. The basis of this formation is represented by unconformity to the Proterozoic and Triassic basement rocks, Neogene Vinh Bao formation and the Early Pleistocene Le Chi formation, whereas the top generally is an unconformity to the overlying Vinh Phuc formation.

Based on lithological and genetical observations in IGPVN drillings as well as archive data, the Ha Noi formation is separated into an upper and a lower part:

- The upper part is composed of fine sediments such as sandy silt, silt and clay. Previous palynological studies indicate that these sediments are deposited in an alluvial to marine environment.

- The lower part can be characterised by dominated by medium to coarse grain size sediments with intercalated silt layers. This sub-formation shows fining-upward characteristics, with a dominant coarse fraction (coarse sand, gravel) close to the basis and an increasing fine fraction (fine sand, silt, clay) with decreasing age. This lower part has alluvial origin and reflects the transition to a more marine environment in the upper part.
4. Integrating Results into a Conceptual Model

Quaternary, Upper Pleistocene – Vinh Phuc formation (Q₁³ vp)

Vinh Phuc formation was established by Hoang Ngoc Ky and Nguyen Duc Tam in 1973 based on outcrops of sediments in Vinh Phuc Province. Based on IGPVN drillings in Nam Dinh area, the Vinh Phuc formation occurs from 35 m to 96 m depth. It has an average thickness of about 30 m, with strongly varying maximum in the south central part of Nam Dinh (Q227, 61 m) and minimum (12 m) close to the adjacent hard rocks in the south west. In the West of Nam Dinh area this formations locally overlies directly the Mesozoic and Proterozoic rocks. In other areas of Nam Dinh (and the whole Red River Delta) it typically has a disconformity to the underlying Ha Noi formation. A disconformity to the Holocene Hai Hung formation is generally found at the top of Vinh Phuc.

The Vinh Phuc formation can generally be divided into 3 parts with different origin:

- **Alluvial Vinh Phuc formation (aQ₁³ vp):** This part can be found only locally in Nam Dinh area. It is characterized by a coarse grain fraction (fine to coarse sand, gravel). Dominating minerals are quartz and mica.

- **Alluvial to marine Vinh Phuc formation (amQ₁³ vp):** This part Vinh Phuc formation represents the dominating facies type in IGPVN drillings. Generally, a fining-upward sequence has been observed and, therefore, two parts can be distinguished:
  - An upper part dominated by fine sediments such as silty clay, probably representing the transition to a marine environment.
  - A lower part containing coarser grain size fraction as fine to medium sand and scattered gravel, representing sedimentation in an alluvial environment.

- **Marine Vinh Phuc formation (mQ₁³ vp):** This sediment does only occur in the south of Nam Dinh area, it has been locally discovered in Nghia Hung district such as in IGPVN boreholes Q227 and Q228. This part mainly consists of clay and silt of marine origin.

Quaternary, Lower to Middle Holocene – Hai Hung formation (Q₂¹⁻² hh)

The Hai Hung formation widely occurs in Nam Dinh area and is locally exposed at the surface. It is generally identified in all boreholes of IGPVN drillings as well as in archive drilling data. Top of the Hai Hung formation can be in depths of down to 37 m. The reported thickness of this formation has an average of about 28 m, but varies strongly with a maximum of 45 m (Q225a) and minimum of about 8 m in the vicinity of outcropping hard rocks in the west. Late Pleistocene sediments of the Vinh Phuc formation are generally met below the basis of the Hai Hung formation and more recent Holocene sediments (Q₂³ tb) at the top.

In own lithological observations based on cores from IGPVN well drillings, two subformations have been described. An upper part with clay, silt and sometimes extensive shell layers, and a lower part dominated by a more sandy silt. Typically, previous studies separate the Hai Hung formation into two subformations (NGUYEN VAN CU et al. 1996):
4. Integrating Results into a Conceptual Model

- The upper Hai Hung formation including fine grained sediments of marine origin, including silt and clay, intercalated with fine sandy silt and clay lenses. Locally, shell layers occur.
- The lower Hai Hung subformation comprising three facies types:
  - Alluvial-marine \((amQ_2^{1-2} \, hh_1)\): Mainly grayish silt and clay with intercalated fine sand layers.
  - Bog-marine \((amQ_2^{1-2}h_1)\): Dark gray silt and clay with varying fine sand and remarkable content of plant remnants.
  - Marine \((mQ_2^{1-2}h_1)\): Brownish grey fine sandy silt and clay, typically contains remnants of gaper shell.

Generally, the sedimentation environments of the Hai Hung formations reflect the marine transgression of the Early Holocene by the succession of a prevailing estuarine environment up to a more littoral, swamp dominated and finally a gulf environment (NGUYEN VAN CU et al. 1996).

Quaternary, Upper Holocene – Thai Binh formation \((Q_2^3 \, tb)\)

Thai Binh formation was established by Hoang Ngoc Ky in 1978 when he described modern Holocene sediments in Hai Phong – Nam Dinh area. This formation has major impact on the geomorphology of Nam Dinh and represents the source rock for most of the agricultural soils. The Thai Binh formation generally overlies the Hai Hung formation with an observed thickness between 37 and 5 m (average 21 m).

From the lithologically and genetically point of view, the Thai Binh formation is divided into three subformations. They reflect the transition from a marine dominated to a more alluvial environment. However, the disturbed cores received from IGPVN only sporadically allowed identifications of the specific subformations.

- **Upper subformation \((Q_2^3 \, tb_3)\), comprises marine, alluvial, boggy and aeolian facies.**
  - Marine \((mQ_2^3tb_3)\): mainly consist of grey fine sand and silt, this facies has been identified in Q226.
  - Aeolian marine sediment \((mvQ_2^3tb_3)\): beach ridge deposits aligned parallel to recent coast (see also Figure 2). Due to eolian sorting processes the sediments are dominated by fine sand.
  - Bog, marine, alluvial sediment \((ambQ_4^3 \, tb_3)\): Unit with alternating facies leading to heterogeneous sediments dominated by brownish grey silty clay and fine sand.
  - Alluvial – marine sediment \((amQ_2^3tb_3)\): These sediments distributed widely in Nghia Hung, Hai Hau District as identified in Q224, Q225, Q227, Q228 and Q229. Their composition included grey fine sand fining-upward to silty clay.
  - Alluvial-boggy sediment \((abQ_2^3tb_3)\): Sedimentary composition was mainly silt and clay with fine sand.

- **Middle subformation \((Q_2^3 \, tb_2)\), marine dominated with alluvial influence:**
4. Integrating Results into a Conceptual Model

- **Alluvial-marine (amQ$_2$³ tb$_2$):** These sediments were discovered e.g., in Q222. Composition contained brown clay with fine sand and sandy silt layers.

- **Marine sediment (mQ$_2$³tb$_2$):** This sediment is widespread close to the surface with a range of fine sand and silty sand. Typical characteristic are remnants of marine snails (operculum).

- **Lower subformation (Q$_2$³ tb$_1$), marine dominated with alluvial-boggy influence:**
  - **Alluvial-marine (amQ$_2$³ tb$_1$):** These sediments are found in Xuan Thuy and Hai hau area. Composition is mainly fine sandy silt and clay.
  - **Boggy-marine (mbQ$_2$³ tb$_1$):** grayish clay with sand and high content of organic material.

### Recommendations, chapter 4.1:

- Structural Features in Nam Dinh are quite complex and are not sufficiently understood due to lack of data. Therefore, it is necessary to pay
  - More attention on the localization of the hard rocks in the West and SW of Nam Dinh, especially the occurrence of T$_1$ Formation.
  - More attention on the identification and localization of water bearing faults, e.g. using VES or other geophysical methods. It would be helpful to clarify their contribution to the groundwater budget in Nam Dinh.

- Depth of Cenozoic basement, in East and South of Nam Dinh is not clear due to lacking data. Seismic studies can shed light on this issue, which is relevant to calculate the total volume of Neogene sediments and pore waters.

- Q$_1$vp formation potentially has key roles to (i.) isolate Q$_1$hh sediments from the surface or (ii.) represent a second permeable unit. To understand its relevance for groundwater exploration, its composition and, thus, vertical and horizontal permeability need to be studied in a regional scale.

- Composition of Q$_2$ sediments is heterogeneous and, due to the focus on stratigraphic point of view, distribution and connection of high permeable and low permeable layers is still not well understood. Thus, a comprehensive interpretation of available archive drilling and well logging data is recommended.
4.2 Hydrogeology of Nam Dinh

The described lithological formations can be divided in hydrogeological units which play a certain role for the hydrogeological regime in Nam Dinh province either as aquifer or aquiclude. According to the Hydrogeological mapping of Nam Dinh (NGUYEN VAN DO 1996a) the Cenozoic formations in the RRD can be distinguished into 5 hydrogeological units, namely Upper Holocene (qh1), Lower Holocene (qh2), Upper Pleistocene (qp2), Lower and Middle Pleistocene (qp1) and Neogene (Pliocene, n), see also. Note that the hydrogeological units may comprise high permeable as well as low permeable sediments within the same unit. Furthermore, adjacent Mesozoic rocks represent important aquifers at the border of Nam Dinh province area. Especially the karstic limestones of the T2 formation represent a high yielding karst aquifer (t2) as reported from Ninh Binh province. The hydrogeological potential of the t1 aquifer has not been studied yet, at least a significant potential has been found in well Q220. The hydrogeological unit of the Proterozoic formations represent an aquiclude (pr).

This study is working on a provincial scale and, therefore, it was not always possible to distinguish five different hydrogeologic units of the Cenozoic strata. Especially, two Holocene and two Pleistocene aquifers could not always be identified in the available data and observed strata. Therefore, when data sets lacking in detail, the hydrogeological units have been summarized to qh (qh1, qh2) and qp (qp1, qp2) aquifer, given the fact that the qh and qp units have at least a local hydraulic connection. It must be discussed in which extend this

<table>
<thead>
<tr>
<th>Geologic unit</th>
<th>Formation</th>
<th>Aquifer type / potential</th>
<th>Hydrogeologic unit</th>
<th>Hydrostrat. Conceptual model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q2 tb1</td>
<td>Thai Binh</td>
<td>Weak pore aquifer, aquiclude</td>
<td>qh2</td>
<td>qh2</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td>qh1</td>
</tr>
<tr>
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<td>Hai Hau, upper</td>
<td>Aquiclude</td>
<td>qh2</td>
<td>qh2</td>
</tr>
<tr>
<td>Q2 hh</td>
<td>Hai Hau, lower</td>
<td>Weak to average pore aquifer</td>
<td>qh1</td>
<td>qh1</td>
</tr>
<tr>
<td>Q1 vp</td>
<td>Vin Phuc, upper</td>
<td>Average pore aquifer</td>
<td>qp2</td>
<td>0vp</td>
</tr>
<tr>
<td>Q1 vh</td>
<td>Vin Phuc, lower</td>
<td>Weak pore aquifer, aquiclude</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Ha Noi</td>
<td>Good pore aquifer</td>
<td>qp1</td>
<td>qp</td>
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<td>Le Chi</td>
<td>Good pore aquifer</td>
<td>qp1</td>
<td>qp</td>
</tr>
<tr>
<td>N4 vb</td>
<td>Vin Bao</td>
<td>Average to good pore aquifer</td>
<td>n</td>
<td>m4</td>
</tr>
<tr>
<td>T2 dg</td>
<td>Dong Giao</td>
<td>Good karst aquifer</td>
<td>t2</td>
<td>t2</td>
</tr>
<tr>
<td>T1 tl</td>
<td>Tan Lac</td>
<td>Weak to average(?) fracture aquifer</td>
<td>t1</td>
<td>t2</td>
</tr>
<tr>
<td>PR sh</td>
<td>Red River</td>
<td>Aquiclude, possibly water-bearing faults and fractures</td>
<td>pr</td>
<td>0PR</td>
</tr>
</tbody>
</table>
4. Integrating Results into a Conceptual Model

Abstraction meets the realistic scenario. Keeping this in mind, the hydrogeologic units have been translated into a hydrostratigraphy proposed for a conceptual hydrogeological model on a provincial scale, distinguishing predominantly low permeable aquitard units (e.g., 0hh2, 0vp,) and predominantly permeable aquifer units (e.g., qh2, qh1, qp, see Table 4). This abstraction was necessary in order to set up a 3D-structural model in preparation of a numerical model (see this report, Part B).

4.2.1 Aquifer Parameterization

Despite of the lack of long-term pumping tests, aquifer parameters have been determined from sediment grain-size analysis (Hydraulic Permeability $K$, Porosity $n$), slug tests (Hydraulic Permeability $K$), and fluctuation of groundwater heads as a response of natural impacts (stoatativity, specific storage). These parameters are relevant for further modelling works (see this report, Part B).

4.2.1.1 Hydraulic Conductivity ($K$), Porosity ($n$, $n_e$)

The applied methods of grain size and slug test analysis are described in chapter 3.2.2 and 3.3, the results are discussed below. Sediments samples were collected from core material of the IGPVN well drillings. Samples include material of each screen depth of the monitoring wells as well as selected non-screened formations. Box plots in Figure 20 show the distribution of the calculated hydraulic permeability ($K$) from grain size analysis (Left) as well as calculated porosity, based on empirical relationships (see chapter 3.3). A complete list of sediment samples and results of grain size analysis is documented in Annex 6.

![Box plots showing distribution of hydraulic permeability K (left, n=19) and total porosity n (n=33) per hydrogeological unit, calculated from grain size analysis of core material collected from IGPVN well drillings.](image)

The hydraulic conductivity values derived from grain size show in all hydrogeological units median values within 1-2x10$^{-5}$ m/s. However, the distribution of $K$ values indicates the higher permeability of qp1 relative to Neogene unit. Furthermore, the high variability of qp2 unit is shown, even when the number of data (n=3) are not sufficient to be representative. The median of calculated porosities varies with in 0.26 and 0.29, with a high variability in the qp1 and qp2 formation up to >0.4. The reason for the different sample number for porosity (n=33) and $K$ (n=19) is the shortcoming in the discrimination of the fine fraction by the grain size
4. Integrating Results into a Conceptual Model

In case the undistinguished residual fine fraction was as high as >10% of the total sample, $d_{10}$ value was considered to be not reliable anymore and $K$ value was not calculated. Therefore, the results are strongly influenced by the type of performed sampling and grain size analyses and the results presented here represent the high permeable aquifer layers in the units, rather than the low permeable aquiclude layers.

In contrary to the empirical grain size analysis, slug test analysis measures directly the aquifer response and, thus, is believed to provide more reliable aquifer properties. The observed aquifer response can be distinguished in two types, the damped (“normal”) case and the underdamped case. The underdamped case is characterized by an oscillatory behaviour of the groundwater head indicating a high hydraulic conductivity of the aquifer and inertial effects in the well (Butler 1998; Butler et al. 2003; Duffield 2007). Figure 21 shows two typical examples from Nam Dinh wells, Q223 (damped) and Q227 (underdamped).

Please note that the porosity calculations above refer to the total porosity volume of sampled formation. For hydrogeological studies the effective porosity ($n_e$) is more relevant, because advective groundwater flow occurs only in the $n_e$ portion. The empirical Marotz-relashionship (chapter 3.3) provides a rough estimation for high conductive (>10^{-5} m/s) aquifers (Marotz 1968, Kollmann 1986). Hereafter, high $K$ values calculated from slug tests are accompanied with $n_e$ values according to Marotz 1968.

All calculated slug test results and the used methods of analysis are provided in Annex 7 and are visualized in Figure 22. According to these data, the conductivity values for $q_{p1}$, $q_{p2}$ and $n$ range within one order of magnitude. Wells screened in $q_{p1}$ aquifer are showing the highest conductivity ($K$) with a median of 7x$10^{-5}$ m/s ($n_e$ 0.03) and maximum $K$ of almost 10^{-3} m/s. Figure 21: Two examples for slug test analysis in the damped (“normal”) case (left: Q223, $K$=2.92 m/day) and underdamped case (right: Q227, $K$=11.19 m/day). Curve fitting has been using AQTESOVL 6.5. The parameter used for the analysis of this two cases are documented in Annex 7. Groundwater heads given as normalized to the maximum displacement in a normal (left), and logarithmic scale (right), respectively.
4. Integrating Results into a Conceptual Model

Even when quite low in number, the \( q_{p2} \) aquifer has a lower \( K \approx 2 \times 10^{-5} \) m/s. The Neogene aquifers conductivity shows a high variability with a median just slightly lower than \( q_{p2} \). Lowest conductivity is reported from \( q_h \) with a median of \( 6 \times 10^{-6} \) m/s, please note that this represents the more permeable strata of the \( q_h \) unit where the wells screens are located. Results from the Triassic units are \( 1.3 \times 10^{-5} \) (Q220, \( t_1 \)) and \( 3.5 \times 10^{-8} \) (Q92a, \( t_2 \)). In case of Q92a this value more likely represents clogging and skin effects of the >15 year old well, since a considerably higher conductivity is expected in the karst aquifer of the \( t_2 \) unit.

A comparison of \( K \) values derived from slug test analysis with previous pump tests in Nam Dinh (NGUYEN VAN DO 1996b) shows that, especially the \( K \) values for \( q_{p1} \) are consistent with the archive data (see this report, Part B). Regarding the units \( n, q_{p2} \) and \( q_h \), own \( K \) values vary to the archive data within one or two order of magnitude. One reason may be the low number of own data unable to provide a representative distribution, especially in the heterogeneous units \( q_h \) and \( q_{p2} \). Another reason is that IGPVN monitoring wells are screened in most permeable layers, whereas the results from previous studies obviously represent both high as well as low permeable layers. This may explain the deviation of the \( K \) values in the units \( q_h \) (\( q_{h1}, q_{h2} \)) and \( n \) (previously \( m4 \)).

Resumably, \( K \) values calculated by an indirect empirical (grain size analysis) and a direct analytical method (slug test) provide quite similar mean values for the \( q_{p1} \) and \( n \) aquifer which generally confirms the suitability of both procedures. Also the results of \( q_h \) and \( q_{p2} \) aquifers are within the same order of magnitude even when not representative in number. However, it seems that the indirect empirical method generally underestimates the \( K \). Further insight provides the direct comparison of \( K \) from sediment samples taken from the screen depth of a well with \( K \) from the associated slug test (Fig. 22, right). While the \( K \) values match quite well in four cases (close to dashed line), slug test analysis provides about one order of magnitude higher \( K \) values in four other cases. Again, the reason is supposed to be in the selected method of grain size analysis and, thus, the slug test data are believed to be more representative.

Figure 22, Left: Box plots of \( K \) values calculated from slug tests in existing and new national monitoring wells. Right: Scatter plot comparing \( K \) values from slug test analysis in wells with \( K \) from sediment samples taken from screened depth (\( n=10 \)).
It has been demonstrated that estimated effective porosities $n_e$ are generally quite low (<10%) even the higher conductive aquifers of the working area. This is relevant for further water budget and numerical calculations and should be confirmed in further studies performing tracer tests or laboratory tests with undisturbed core samples.

### 4.2.1.2 Storativity ($S$) and Specific Storage ($S_s$)

Determination of an aquifer’s storativity is crucial for further groundwater volume and water balance calculations as well as modelling of groundwater abstraction and drawdown. While long-term pump tests are the classical method to determine the storage coefficient, in this study storativity has been derived from two alternative methods, based on the determination of the barometric efficiency (BE) using Clark’s method (Clark 1967), and based on the tidal effect on groundwater heads using “time lag” and “diffusivity” method (Jacob 1950). The applied methods are described in chapter 3.2.3 and 3.2.4, the results are discussed below.

The impact of atmospheric pressure fluctuations to confined aquifers in Nam Dinh area is clearly shown in Q221, the monitoring well with largest distance from the coastline (Figure 23, left). Obviously barometric fluctuation is the major driver for groundwater level fluctuation in a short-term and, thus, Clark’s method provides a good fitting trend line in the summation

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Figure 23, left: Time series of groundwater head versus barometric pressure fluctuation in Q221b (both in m H$_2$O). Right: Estimating barometric efficiency based on measured-head data from Q221b. The top row shows raw data and summation plot from 10th April 2011, whereas the bottom shows the same from 10th May 2011. Average BE is 0.58 (58%).
4. Integrating Results into a Conceptual Model

plot of changes in water level and barometric pressure (Figure 23, right). The two examples in Figure 23 proof the reproducibility of the well-specific BE determination in different time periods. Other wells of Nam Dinh show groundwater heads fluctuation superimposed by other external impacts, such as tidal fluctuation, groundwater abstraction, and others. Clarks method includes simple processing to filter the barometric effect on groundwater heads and, thus, BE was determined for 10 monitoring wells. However, the method was not successful in other wells, probably due to predominant external (such as tidal) effects, e.g., in well Q222b and Q225b.

The calculated results for BE are documented Annex 8 and visualized in Figure 24. Generally, BE ranges within 0.14 and 0.7, the highest value marks Q220 (t1). The calculated
BE values reflect typical behaviour of confined aquifers. The increased atmospheric pressure tighten the pore spaces in the overlying soil and produce a capillary effect as the groundwater water level rises in response to compensate the increasing pressure. The smaller BE (~0.2) in Neogene aquifer reflects the deeper aquifer which is barometrically more isolated from the relatively small change in level that barometric influences can produce. The high BE in qh aquifer (here qh1) can be explained that a barometric pressure change results in a more equivalent or highly proportional drop or rise in groundwater pressure. The BE also indicates the still confined character of qh1, since for unconfined aquifers a BE between 0.8-1 is expected. Subsequently, storativity has been calculated from the BE data as a characteristic for the aquifers elasticity (see chapter 3.2.4). The results are summarized in Table 5 and discussed at the end of this subchapter.

In vicinity to the coastline, tidal fluctuation of confined groundwater heads is much more dominant than barometric effects. Ba Lat surface water station at the Red River mouth provides tidal fluctuation data for Nam Dinh. In comparison with the open sea station in Ho Dau island, Ba Lat station show a similar tidal period but lower amplitude due to the interfering Red River flux (Figure 25, top left). Therefore, the tidal period data from Ba Lat together with the maximum tidal amplitude of Hon Dau (2h0 = 3.3 m) is believed to be representative for the coastline of Nam Dinh and used for further calculations according to JACOB 1950 (see chapter 3.2.4). Selected time series from December 2010 clearly show that the fluctuation of the groundwater heads of the wells Q225b (qp2) and Q226a (qp1) are driven by the tidal fluctuation of the nearby open sea, the time lag in both sites are within 6 and 11 hours (Figure 25). Furthermore, the time series of Q226a (Figure 25, bottom left) indicates another interfering impact with a different period and weaker amplitude, resulting in a modified time series and occasionally double peak. Further analysis was based on time lag

<table>
<thead>
<tr>
<th>Well</th>
<th>Aquifer</th>
<th>S</th>
<th>b (m)</th>
<th>S_b (1/m)</th>
<th>Method</th>
</tr>
</thead>
<tbody>
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<td>Q220T</td>
<td>t1</td>
<td>8.02E-05</td>
<td>60</td>
<td>1.34E-06</td>
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</tr>
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<td>30</td>
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<td>4.21E-04</td>
<td>*60</td>
<td>7.01E-06</td>
<td>BE method</td>
</tr>
</tbody>
</table>

Table 5: Summary of storativity and specific storage calculated from BE and tidal effects (JACOB 1950).
as well as the difference between the maximum and minimum groundwater heads (oscillation range, \(2h_x\)) at each monitoring well over a complete tidal cycle (12.4h).

The largest groundwater oscillation range was measured in Q225b (0.145 m), a site close to the coastline as well as the Red River mouth and the smallest range in Q226a (0.029 m). The groundwater head in Q222b (qp\(_1\)), located quite far from coast but 0.9 km close to the Red River bed shows a clear tidal impact with 0.14 m amplitude. This relatively strong impact cannot be related to the open sea, but to the Red River and therefore the maximum local River level amplitude (\(2h_0 = 0.98\) m, Station Nam Dinh) has been considered for further calculations in case of station Q222b. Thus, the discussed examples illustrate the tidal impact to groundwater heads in Nam Dinh area, which is strongly depending on the specific site and vicinity of surface water bodies. Groundwater fluctuations in other sites which are not discussed here, are not only influenced by one predominating, but by several overlapping and interfering signals of different periods and amplitude resulting in double or triple peak time series. More sophisticated data analysis may be able to identify and distinguish the site-specific source signals and should be envisaged in further scientific studies.

Estimated time lag and amplitude data as discussed above have been used for calculating site-specific storativity (\(S\)) and specific storage (\(S_s\)) based on the time lag and diffusivity model from JACOB 1950. As indicated by the analytical solution in chapter 3.2.4, both methods require site-specific transmissivity (\(T\), m\(^2\)/s) data, which are calculated by aquifer thickness and K derived from slug test analysis. The results are summarized Table 5 and Annex 8 and discussed below in comparison to \(S\) derived from BE (see above). The station Q226a provides a direct comparison of the different methods. While tidal derived \(S\) are matching quite well, BE derived \(S\) is about two times higher. A statistic comparison of storativity data for qp aquifer (Figure 26, Table 6) provides a slightly lower median of the tidal derived \(S\) (time lag + diffusivity) but represent still a good match to BE derived \(S\). This confirms the suitability of the two methods. Nevertheless, uncertainties of the results are expected due to the strong abstraction of the applied analytical model in Jacobs solution. Furthermore, due to the calculation using K data from slug tests, skin and other well effects may be reproduced in the tidal derived \(S\). As recapitulation, \(S\) derived from BE as well as

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<th>Method</th>
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</tr>
<tr>
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<td>qp</td>
<td>6.7E-05</td>
<td>qp - BE</td>
</tr>
<tr>
<td>qp</td>
<td>5.29E-05</td>
<td>qp - Tidal</td>
</tr>
<tr>
<td>qh1</td>
<td>3.2E-05</td>
<td>qh1 - BE</td>
</tr>
</tbody>
</table>

Table 6: Median S values calculated from BE and tidal fluctuation (see figure 26).
tidal effects fit quite well in the normal range for confined aquifers assumed to be within $10^{-5} – 10^{-3}$. Highest $S$ values ($4.2 \times 10^{-4}$) are calculated for the $n$ aquifer, representing high pore water pressure in the grain skeleton, and, consequently lowest ($3.2 \times 10^{-5}$) for $qh$ aquifer. The median of $S$ and $S_s$ data provided for further modelling studies are given in Table 6.

### 4.2.2 Groundwater Dynamics

Operating by CWRPIN since 1995, the national groundwater-monitoring network represents an important observation source providing groundwater quantity and quality data for more than 15 years. The national monitoring network in Nam Dinh comprises 5 stations Q107, Q108, Q109, Q110 and Q111, comprising 10 monitoring wells screened in the three hydrogeological units $qh$ ($n=5$), $qp$ ($n=3$) and $n$ ($n=2$). Long-term monitoring shows that groundwater level fluctuation are caused by natural factors (climate and hydrological factors) as well as anthropogenic impacts such as groundwater extraction, lake and canal construction, irrigation and drainage systems.

The long-term time series of monthly averaged groundwater level data illustrate some major impacts of these factors. According to the behaviour of level fluctuation, the screened aquifers can be allocated to two hydraulic groups (Figure 27). The shallow $qh$ aquifer shows a stable trend since begin of data collection in 1995. Deficits in the Holocene groundwater budget are balanced by recharge in frame of repetitive phases of irrigation and inundation. Previous modelling studies suggest a recharge up to 100 mm/a in $qh$ units covered with confining clay layer (LARSEN et al. 2008). The seasonal amplitude of up to one Meter indicates a close hydraulic connection with nearby rivers and channels. Q111 even shows a slightly increasing trend, possibly originated in local subsidence or increasing sea level. The second hydraulic group is represented by the time-series of $qp$ and $n$ aquifers indicating

![Figure 27: Time-series of monthly averaged Groundwater level of Holocene (qh), Pleistocene (qp) and Neogene (n) aquifers, manually measured in National Groundwater Monitoring Wells in Nam Dinh province since January 1995 (Data source: CWRPI).](image-url)
hydraulic connected aquifers. Obviously, the increasing exploitation of groundwater since the 1990ies results in a decreasing trend of groundwater levels in both Pleistocene aquifers of 0.4 m/a (Q108, Q107) up to to 0.6 m/a (Q109). Previously, groundwater levels of deeper

Figure 28a, b, c: Time series of daily averaged Groundwater level derived from automatic transducer measurements in Holocene (qh), Pleistocene (qp) and Neogene (n) aquifers in Nam Dinh. Automatic data collection started in September 2010 with an interval of 1h.
Pleistocene and Neogene aquifers in S Nam Dinh have been reported to be artesian in earlier years (DONRE, communication by mouth). The illustrated time series of groundwater level fluctuation is a typical example for the situation in Nam Dinh and shed some light on groundwater dynamics in this province. Shallow groundwater (qh) receives a significant amount of recharge due to hydraulic connection with river, tributaries and irrigation channels. It can be concluded that at the transition of the units qh - qp, low permeable aquicludes separate the relatively isolated hydraulic system of unit qh and units qp – n. Assuming the majority of abstraction wells are screened in qp aquifer, the similar behaviour of qp and n indicates a close connection on a regional scale. At the site with the strongest observed groundwater drawdown (Q109), a relatively high hydraulic head in n is observed indicating a flow recharge of qp from n aquifer.

A closer look to more recent groundwater heads provide daily averaged data from IGPVN monitoring wells between September 2010 and Mai 2011 (Figure 28a-c). Please note that the groundwater head “fluctuation” since Feb-2011 in Q228b (Figure 28a,c) and Q223a (Figure 28b) is due to a temporary malfunction of the pressure transducer equipment. The relatively short time span of 8 months is not sufficient to observe general trends. However, the attempt of interpreting level and fluctuation of hydraulic heads is presented below.

Figure 28a shows groundwater head from wells screened in the shallower aquifers qh1 and qp2 aquifer. The qh aquifer generally shows shallow groundwater level about -1 m asl. At the very coastal location of Q225 also the qp2 aquifer have similar hydraulic head, whereas in location Q228 qp2 aquifer have a definite lower head comparing to qh in the same location, representing a different hydraulic unit probably facing drawdown due to groundwater abstraction. In both locations Q225 and Q228, qp2 aquifer has a higher hydraulic head than qp1 aquifer indicating that an aquiclude at least locally separates both qp units.

Figure 28b represents hydraulic heads wells screened of the deeper qp and n aquifers in N and E of Nam Dinh. The heads vary within -1 m asl in the north (Q221) to -2 - -3 m asl in the central E and SE part. Generally the hydraulic heads in qp and n are very similar, especially in Q221 and Q226. Assuming that artificial connections due to bad well design can be excluded, these heads indicate close hydraulic connection of qp and n units. Possibly, the increasing head in Q223n is again due to equipment malfunction which will be confirmed in frame of future data readouts.

Figure 28c shows hydraulic heads of monitoring sites screened in W and SW Nam Dinh. The data from the deeper aquifers (n, qp) of this area strongly reflect drawdown, similarly to the data of the National Monitoring Wells (Figure 27). The lowest heads are found in qp1 and n aquifers in the SW of Nam Dinh (Q228, Q229) with -7 - -8 m asl, assuming a “natural” groundwater level similar to qh1 in Q228c or even higher. Also the qp2 unit in Q228b even reflects drawdown in comparison to qh1 in Q228c but in a much lesser extent, indicating again the weak hydraulic connection between qp1 and qp2 units. With about -4 m asl also the qp1 unit at site Q227 is facing groundwater decline. Similar behaviour of their time series in qp1 and n units at Q227, Q228 and Q229, e.g. the maximum in April 2011, indicate that same in- and outflow mechanism regulate local groundwater budget, which are not dominant.
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Further north and west, the hydraulic head in the adjacent Tertiary aquifers with +1 m asl is quite high, represented in Figure 28c as Q220 ($t_1$) and confirmed by data from National Monitoring Well Q92a ($t_2$).

A clearer picture about the spatial relationship is given by thematic contour maps focusing spatial groundwater head distribution in qp1 and n aquifer at the end of the dry season May 2010 as well as the end of the rainy season in November 2010. Instead of the widespread Kriging-Method, data have been interpolated using the Natural Neighbour method, which does not extrapolate in areas without data and not to extrapolate Z grid values beyond the range of data. However, unrealistic boundary effects due to lacking boundary conditions cannot be excluded locally without manual editing of the contour maps.
The contour maps of hydraulic heads in qp aquifer (Figure 29) clearly visualize the spatial extend of groundwater abstraction, indicated in the time series data discussed above. Due to long-term extraction, a regional abstraction cone has been developed in the south of Nam Dinh which has its maximum depth in Q109 with up to -8 masl deep. This confirms the information that groundwater is intensively used in S Nam Dinh, but surface water in the N and E (local DONRE and PC, monthly communication). In November 2010 the cone even is slightly extended which is most obvious in its central part. This extension during the rainy season is not astonishing, since the qp aquifer is supposed to be quite isolated from surface recharge. A general groundwater flow direction is assumed to be NW-SE, nevertheless, this natural flow is altered by human activity nowadays directed towards the abstraction cone. Even an infiltration of saline seawater cannot be excluded on a long term. On the other hand the strong hydraulic gradient in the western part of Nam Dinh indicates a side-flow from the adjacent Triassic rocks.

The contour plot for Neogene unit provides a quite similar picture (Figure 30). Please note that in this plot, the hydraulic heads in Q220 and Q92 are considered following the geological cross sections indicating a hydraulic connection to the adjacent Triassic rocks (see Figure 18). Similarly to the qp aquifer, an groundwater abstraction cone evolves in the southern part of Nam Dinh with its centre in Q109 (-7 m asl) and even deepens in November 2011. It can be concluded that the overexploitation in qp unit is fed by the deeper n unit. This is a dynamic and ongoing process continuously extending the regional abstraction cone in n as well as qp aquifers.

Owing to low hydraulic gradients, horizontal groundwater flow velocities in the permeable layers of qh as well as qp and n are generally rather low. Based on median hydraulic conductivity K from slug tests (7x10\(^{-5}\) m/s) and the observed hydraulic gradient in NW and NE (see Figure 29, Figure 30), horizontal groundwater DARCY-velocity (\(v_{DARCY}\)) in high permeable layers of qp\(_1\) unit is within 0.6 - 0.9 m/a. Similarly calculations for relatively high permeable layers of the n unit (median K 1.5x10\(^{-5}\) m/s) provide horizontal \(v_{DARCY}\) between 0.15 – 0.2 m/a, respectively. This is within the range of the apparent (DARCY) vertical flow velocity 0.5 m/a, interpreted from \(^3\)He/\(^3\)H dating in sandy layers of shallow Holocene formations further north in the RRD (POSTMA et al. 2007, see also chapter 4.3.3).

This subchapter presented a consistent and alarming picture on the hydraulic situation of deeper aquifers in Nam Dinh province. However, it must be stated that, in comparison to the size of the observed area, available monitoring data in Nam Dinh and adjacent areas are still quite limited. Local groundwater management should make decisions based on a more detailed picture of the groundwater declination in deeper aquifers. Therefore, it is recommended to supplement the presented (national) monitoring data by manual measurements in local monitoring and household wells which should be carried out minimum twice per year.
4.3 Hydrogeochemistry of Nam Dinh

This subchapter supplements the earlier presented geologic, hydrogeologic and hydraulic aspects with the hydrochemical point of view in order to get further insight into origin and transport pathway of pore waters in the hydrogeological units in Nam Dinh area. This picture presented below is mainly based on the sampling of already existing and new (IGPVN) monitoring wells in Nam Dinh and Ha Nam province, carried out in Mai 2010. The data set comprises a full analysis for each sample, including major composition and trace constituents as well as isotopic studies in selected samples (chapter 3.4). Furthermore, archive data have been integrated to assess the salinization status of Holocene and Pleistocene aquifer.

4.3.1 Hydrochemical Characterisation

Composition of major anions and cations in water can be determined with relatively low technical efforts and costs. The predominating major composition may differ within one hydrogeological unit which can be used to distinguish local inflow or ongoing

Figure 31: Piper diagram visualizing major chemical water composition of hydrogeological units in Nam Dinh and Ha Nam (Q92) area, sampled in old and new monitoring wells in Mai 2010 (n=43, collected from 22 sampling sites). Note that maximum symbol size represents TDS 10 g/L despite of observed maxima up to 23 g/L in Q111.
4. Integrating Results into a Conceptual Model

Hydrogeochemical processes. A Piper diagram has been used to visualize the major groundwater chemistry in two triangular diagrams representing cations and anions, both integrated into one rhombus diagram (see Figure 31).

Based on the origin of the samples and their arrangement in the Piper plot, distinct hydrochemical groups can be defined. The samples taken from tertiary units mark two distinct groups with different composition. T2 with (Mg,Ca)Na-Cl hard rock shows surprisingly high Na-Cl content for the suspected limestone karst aquifer. Nevertheless, the very low SiO2 content (3.2 mg/L, see Annex 9) and lowest Ca/Mg meq ratio (~1) underlines dolomite or high-Mg calcite dissolution, the saline impact of unknown origin is confirmed by previous studies (NGUYEN VAN DO 1996a). Q220 well was supposed to be drilled in the same t2 unit, but a much different water composition (Na-HCO3-SO4), this well is believed to be screened in sand- and siltstones of the t1 unit. Furthermore, high sulphate (100 mg/L) and fluoride (1.2 mg/L) content possibly indicates the influence of deeper sulphuric groundwater from the nearby Song Hong fault zone (see Figure 16).

Further “end links” in the Piper plot are marked by high saline Na-Cl sea water, strongly influencing pore water in coastal shallow aquifer (Q111, TDS 23 g/L) and the low saline river water (TDS 0.2 g/L) consisting mainly of Ca-Mg-HCO3. Remarkable sulphate content indicates the discharge of domestic or agricultural waste water into channels and rivers. Unconsolidated aquifers in n, qp and qh with relatively high to very high salinity are aligned in the vicinity to the sea water group (Figure 31), indicating the strong impact of high saline Na-Cl water in all units. However, a very distinct group with low saline Na,Mg(Ca)-HCO3 groundwater has been sampled in the deeper qp and n aquifers. A transition group (dashed line Figure 31) close to the high saline group represents the mixing of low saline with high saline Na-Cl water.

Scatter plot in Figure 32 confirms that high saline Na-Cl water is not only widespread in the shallow aquifer, but also occurs in the qp aquifer and to a lesser extend in n aquifer. The majority of sampled water plot close to the typical sea water ratio (molar Na/Cl = 1), or even show higher chloride content due to cation exchange and sorption of sodium. Furthermore, the plot underlines the unique character of low saline qp and n waters in Nam Dinh with high-Na and low-Cl water (Figure 32, dashed line). The molar Na/Cl ratio of Q220 site (t1 unit) suggests a genetic relationship between t1 formation and the low saline water in qp and n aquifers.
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The spatial relationship of the water distribution in qp aquifer is visualized using maps with pie and stiff diagrams (Figure 33 left and right). Pie diagrams show the relative proportion of the constituents (% meq/L), whereas stiff diagrams focus the absolute content (meq/L). A comparison of both maps demonstrates a significant hydrochemical zonation in qp unit which is also the case in n unit even when in a lesser extent. In Red River area along the E border of Nam Dinh high saline pore waters have a Na-Cl dominated composition. However, qp and n units bear low saline pore waters in W and S of nam Dinh province with predominantly Na-Mg-HCO3 composition (Figure 33). A trend of decreasing Ca and increasing Na can be explained by cation exchange processes triggered by groundwater freshening. A comparison of this picture with the observed groundwater head drawdown As shown in the scatter plot (see Figure 29) points out that the low saline pore water of qp unit in S and W Nam Dinh is subject of intense groundwater abstraction resulting in the strong observed drawdown.

Furthermore, a closer look to Figure 33 reveals, that low saline pore water in qp even has a significant chloride content in the W, which is not the case in S of Nam Dinh. This indicates minimum two different sources (high-Cl and low-Cl) feeding the qp unit with low saline water, since chloride as a conservative tracer does not faces absorption or retention processes.

The limited hydrochemical data of n unit indicate a similar picture to the discussion above for qp unit. This supports the hypothesis of a good hydraulic connection between both units indicating both aquifers are fed by similar recharge mechanisms. According to the argumentation above, recharge mechanisms of qp and n are quite different in the S comparing to the NE and E of Nam Dinh. This confirms similar assumptions derived from fluctuation of hydraulic heads Q227, Q228, Q229 (see Figure 28). Since brackish and saline qp pore water occur in NE and E Nam Dinh, the recharge of fresh groundwater most likely originates from the western Triassic formations as shown in Figure 33. The absence of chloride in the center of the qp fresh water favours t1 to be the major contributor. However,
the specific contributions of $t_1$, $t_2$ and/or water-bearing faults must remain unclear at this point.

This subchapter concludes with an interpretation of the observations above in terms of origin and genesis of groundwater in Nam Dinh, summarizing Figure 31 and Figure 33. Four groups with distinct hydrochemical pattern mark the four end members of two assumed mixing lines: $t_1$, $t_2$, surface and sea water (Figure 34). $T_1$ water type feeds $q_p$ and $n$ units with low saline (low Cl) pore water in S Nam Dinh (Q227, Q228, Q229, Q109a). Whereas low saline $t_2$ (relatively high Cl) water type (Q92a) mixing with surface water (Q92) contributes to the Center of Nam Dinh (Q108b). Thus, two pathways have been identified to feed freshwater lens in Nam Dinh. With increasing distance from W to E and, thus, residence time, Na-Cl is the predominant water composition approaching to sea water, the end member of both the mixing lines (Figure 34).

The unit not discussed yet in detail, $q_h$, does not show a significant spatial trend in its composition. The available data only show a heterogeneous distribution with the local predominance of high saline Na-Cl waters (data not shown). Nature and origin of salinity in $q_h$ as well as deeper $q_p$, $n$ units is focus of the next subchapter.

### 4.3.2 Groundwater Salinity

Salinization of groundwater is a major issue in Nam Dinh and generally a limiting factor for groundwater use in $q_h$ units as well as in $q_p$ and $n$ units in the N and E of Nam Dinh. As shown before, low saline fresh groundwater results in extensive groundwater abstraction and use in S Nam Dinh. A closer look to previous and recent spatial distribution as well as insight in the origin of high salinity is given below. Herewith, the terms “fresh”, “brackish” and “saline” expresse a specific range in total dissolved solids (TDS) and used as defined below:

- **Fresh water**: TDS < 1,000 mg/L, sufficiently dilute to be potable
- **Brackish water**: TDS 1,000 - 20,000 mg/L, generally too saline to be potable, but significantly less saline than seawater
- **Saline water**: TDS >20,000 mg/L, similar to seawater (~35,000 mg/L)
Additionally, it is common practice in Vietnam to distinguish a fraction with TDS 1,000 - 3,000 mg/L, representing low brackish water still usable for specific purposes other than drinking water.

Archive data from field survey of domestic household wells during rainy and dry season 1999 and 2000, collected by HOANG DUC NGHIA 2008, have been used to receive a detailed picture about the spatial salinity distribution in qp aquifer. Figure 35 presents these data in a contour plot together with own data from Mai 2010 (coloured symbols) and the salinity boundary determined in frame of the hydrogeological mapping (Do 1996b) and by geomagnetic and georadar studies in 2009 (NGUYEN VAN DAN et al. 2009).

Generally, the 1 g/L saline boundary from the oldest source (1996) roughly fits to the picture observed in 2000 or even in more recent time. Archive data from 1999/2000 may not always represent TDS in qp pore waters, considering simple applied sample procedures and possibly unsure well screen depths. However, the salinity distribution map based on these data (Figure 35) clearly shows the extension of a specific area containing low saline (<500 mg/L) fresh pore water in qp unit surrounded by brackish water reaching a maximum salinity of >5 g/L close to the Red River. Own data from 05/2010 generally confirm this picture, but
indicate locally increasing salinity, such as in E boundary of the freshwater lens (Q226). Own observations do not confirm brackish qp pore waters in W Nam Dinh suggested by archive data (see Figure 35), however, old as well as new data are limited in that area. The study of NGUYEN VAN DAN et al. 2009 concludes in the mapping of the 1 g/L salinity boundary in qp aquifer based on geomagnetic and georadar studies. This boundary matches well with old and new hydrochemical data in the central part, but does not in E as well as in W central area of Nam Dinh. However, even when these geophysical methods are generally applied for shallow aquifers (<40 m bgl), the applied modifications and the accuracy of the results are not discussed here. Generally, the transition between fresh and brackish pore waters is assumed to be quite sharp. Therefore, continuous monitoring of the transition area (see Figure 35) is necessary to quantify the movement of the salinity boundary.

The 2D salinity distribution map (Figure 33; Figure 35) suggests that high saline Na-Cl groundwater is approaching from the Red River area in NE and E Nam Dinh. The question about the salinity distribution in the vertical dimension should confirm or neglect this thesis. In this frame, geophysical well logging has been carried out in IGPVN monitoring wells and especially the induction well logging data provide further insight to this issue. The induction well logging has been carried out by HUMG-GEUS in 03/2010 and results are documented in Annex 2. Some conclusions of these data presented below; a more detailed interpretation of inductive well logging with special respect to groundwater salinization from Red River in Nam Dinh will be published in HOAN V. HOANG et al. (in prep.).

![Figure 36: Variation of resistivity/conductivity in different rocks groups (adapted from PALACKY 1987).](image)

The induction logging measures the formation conductivity which is inversely related to the resistivity. An overview about characteristic formation conductivities provides Figure 36. Please note the typically low conductivity of sand, gravel and sandstone (0.1-20 mS/m), comparing to clays and shales (10-300 mS/m). The main reason is the higher content of high conductive surfaces as a result of a typically higher porosity as well as cation exchange capacity CEC (WAXMAN et al. 1968). However, the presence of saline pore waters (>1000 mS/m) will superimpose the bulk formations conductivity comparing to fresh pore water. Therefore, induction logging qualitatively represents vertical pore water salinity profiles making this method very valuable in groundwater exploration studies. Note that, it is possible
4. Integrating Results into a Conceptual Model

Figure 37: Scatter plot of pore water conductivity versus bulk formation conductivity (left; \( r^2 = 0.97, n=20 \)) and calculated total dissolved solids content (right, \( r^2 = 0.99, n=31 \)), demonstrating a good linear correlation in case of high conductive pore water as well as low conductive pore water down to 1 mg/L.

to distinguish between sand and clay in fresh water formations based on formations conductivity or resistivity, which is not the case in high saline formations.

Bulk formation conductivities have been compared with own water conductivity data measured during the sampling campaign Mai 2010, representing the pore water conductivities in well screen depths. A scatter plot of both data sets suggests good linear correlation \( (r^2 = 0.97, n=19) \) which indicates that the bulk formation conductivities of the observed sediments are mainly driven by the salinity of the pore water (Figure 37). The correlation with calculated salinity (TDS) content fits less in case of low saline pore waters (Figure 37, right). This can be explained by the lower equivalent electrical conductivity Na-HCO3 dominated low saline waters (1 meq/L ~100 µS/cm) in contrary to high saline Na-Cl waters (1 meq/L ~120 µS/cm, APPELLO et al. 2009). Please note that the studied monitoring wells are screened in the high-permeable strata with a relatively low content of the finer fraction. However, the linear fitting indicates a significant formation conductivity of ~90 mS/cm, assuming a very low saline pore water of (<0.1 mS/cm). This seems remarkably high comparing with typical ranges of sediments (Figure 36) and may be explained by ubiquitous clay minerals generated in frame of weathering of the young immature sediments providing surfaces of high electric conductivity. Furthermore, the generally observed high content of mica minerals contributes to the high conductive surfaces in the sandy layers, which obviously results in relatively high formation conductivities similar to clay sediments. Consequently, it is assumed here that the depth oriented variation of the observed formation conductivity is mainly driven by the pore water salinity rather than the variation in grain size.

Facing a lack of pore water salinity data from formations outside the well screen depths, an attempt of a quantitative interpretation of formation conductivity data is presented here even when pore water conductivities are not known. In case of confined, water saturated aquifers, the “bulk” formation conductivity is a product of the conductivities of the solid material as well as the liquid of the pores. In sandy formations the influence of porosity on the formation conductivity can be estimated by ARCHIE’s empirical law, relating the total (or “effective”)
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Electrical conductivity $\sigma_t$ of a rock sample containing water with conductivity $\sigma_w$, to the sample's porosity $n$ and its water saturation (ARCHIE 1942). Assuming water saturated material, ARCHIE’s law can be expressed as (KNIGHT et al. 2005):

$$\sigma_t = \left(1/a\right) \cdot n^m \cdot \sigma_w$$

with $\sigma_t$ as bulk conductivity, $\sigma_w$ connate water conductivity, $n$ total porosity, and cementation factor $m$, which is reported for unconsolidated material about 1.2 for spherical particles, typically 1.3-1.6 for sands and near 1.85 for platy particles (EOS 2011). The tortuosity factor $a$ ranges within 0.62 and 2.45 (KNIGHT et al. 2005) and chosen to be 1 due to lacking data. Thus, ARCHIE’s law can be used to estimate pore water conductivity in a sandy saturated aquifer if formation conductivity and porosity is known, as demonstrated in the example below. Note that Archie’s law is not valid for materials with high content of clay minerals. The WAXMAN-SMITS equation (WAXMAN et al. 1968) has been developed for shaly sands and has proven to be more appropriate for this case due to its consideration of the CEC.

Figure 38: Cross section 5 (location Figure 17) showing depth profiles of the natural gamma (API) and the formation conductivity (mS/m) measured by induction logging. Orange colour indicates well screen depths and measured pore water conductivity (mS/cm). The dashed line indicates the estimated boundary of marine dominated Holocene to alluvial dominated Pleistocene formations, arrows the direction of diffusive transport.
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Figure 38 shows section 5 crossing qp and n aquifer with fresh pore water in SW part up to brackish pore water in the NE. Four formation conductivity depth profiles are plotted for stations Q228, Q227, Q226 and Q225, derived from Induction logging data. As discussed above (see Figure 37) the plots are interpreted here to represent salinity profiles. Even in low saline formations (e.g., Q227), a changing clay content, indicated by natural gamma and confirmed by lithological description, shows only minor impact to the formation conductivity. Consequently, high conductive Holocene formations indicate the existence of high saline pore waters in the Holocene Thai Binh and Hai Hung formations. These formations mainly consist of marine fine grained sediments with high silt and clay content, occasionally intercalated with sandy layers. Due to lacking CEC data, ARCHIE’s law may be applied here only to calculate pore water salinity for sandy layers.

In the alluvial dominated Vin Phuc formation, bulk conductivity $\sigma_t$ generally decreases with increasing depth within 100 – 200 mS/m. Variations in this range can either result from changes in formations grain size or in the pore water salinity (see Figure 36). The underlying alluvial Ha Noi formation shows generally low minimum bulk conductivities <100 mS/m in the W ($\sigma_t$ = 80mS/m in Q227, 95 mS/m in Q228, 105 mS/m in Q229), increasing westward to 130 mS/m (Q226) at the transition zone from fresh to brackish pore water up to 200 mS/m (Q225, compare with Figure 35).

Since pore water conductivity $\sigma_w$ measurements are available from well screen depths in Mai 2010, the validity of ARCHIE’s law and the applied parameter can be tested considering the measured bulk conductivities (see above), measured fluid conductivities ($\sigma_w$ = 47.8 mS/m Q228a, 48.2 mS/m Q227a, 364 mS/m Q226a, 603 mS/m Q225a) and calculated median porosity 0.29 and m = 1.5. This results in 10 times lower calculated pore water conductivities as measured in lowest saline formations (Q227, Q228), up to two times lower as measured in higher saline sites Q226 and Q225. Reasons for these errors are possibly the abundance of clay minerals such as mica, providing high conductive surfaces even in well sorted sandy layers. Further reasons may be the lower molar conductivity of non-chloride ions (APPELO et...
al. 2009) which dominate low-saline pore water chemistry as well as an unsatisfying estimation of the complex geometric formation property \( n' \).

Given the fact that all wells are screened in permeable sandy formations ARCHIE’s law has been applied to compare calculated to measured pore waters conductivities \( \sigma_w \) (Figure 39). The linear fitting suggests a correction of calculated \( \sigma_w \) which has been applied to estimate pore water salinities in the sandy formations of the working area based on total “bulk” conductivity measurements. This approach is supposed to be appropriate to for higher saline sandy formations, but to a lesser extend to low saline and clay rich formations. It must be confirmed and précised by direct pore water measurements especially in clay rich formations. However, Archie’s law combined with a simple linear correction has been used to improve the conceptual understanding of possible saline sources, as demonstrated below.

Maximum formation conductivities \( \sigma \approx 1200 \text{ mS/m} \) have been observed widespread in the Holocene formations (e.g., Q224, Q22, Q228, Q229; Figure 38). Application of the correction provides calculated/corrected pore water conductivities \( \sigma_w \) up to 41 mS/cm, which is close to the electric conductivity of modern sea water (\( \approx 50 \text{ mS/cm, } 25^\circ C \)). The predominant marine sedimentation environment during early and middle Holocene (see chapter 4.1.3) suggests that paleo-sea water was enclosed during the marine transgression and sedimentation and, thus, represent the primary cavity fillings. Note that highest formation conductivities have been observed in marine clay and silt sediments which most likely have a higher conductivity than sandy formations. Thus, the linear approach here probably overestimates pore water salinity in high conductive and clay rich formations (Figure 39, right).

Further North of Nam Dinh province bulk conductivities in Holocene Thai Binh formations decrease significantly (Q223 up to 700 mS/m, \( \sim 300 \text{ mS/m Q221} \)). Consequently, pore waters in Thai Binh formations are calculated to reach up to 23 mS/cm and 8 mS/cm, respectively, indicating predominant brackish sedimentary environment in the N of Nam Dinh during the late Holocene. However, the applied calculations of pore fluid data are based on empirical relationships and need to be confirmed by solid and fluid analysis from undisturbed Holocene samples (HOAN V. HOANG et al. in prep.).

The shape of the formation conductivity profiles provide further insight into vertical movement of saline pore waters when interpreted as typical diffusion profiles. Since advection may be neglected in fine grained sediments, diffusive transport is the dominant transport process driven by the specific concentration gradient. Diffusion profiles with asymmetrical shape and a long slope downwards is found in Q228 and Q227 representing a high concentration gradient to the underlying pore waters (Figure 38). The more symmetrical shape in Q225 stands for a lower salinity gradient of the pore waters from Holocene to Pleistocene formations. Since diffusive transport in clay formations requires a stable concentration gradient in a long term, very low saline pore water in qp (and n) unit in SW Nam Dinh already must have existed during the Holocene marine transgression time if not much earlier. Thus, downward and, in a lesser extent, upward diffusion is believed to be the main driver of salinity (Na-Cl) transport, indicated by arrows in Figure 38. This explains the existence of brackish aquifers not only in qh1 and qh2 but also in deeper qp and n aquifers. The fresh
water aquifers in S and W Nam Dinh only exists due to the continuous side flow of fresh groundwater flushing saline waters to the East as well as coastward. Thus, increasing groundwater abstraction threatens to interrupt or even inverse the flushing process.

Transferring the calculated fluid conductivity data into salinity mass concentrations in terms of Na-Cl, application of Fick’s laws can provide further insight into the timescale of diffusive transport. Fick’s first law can be used to estimate the steady state diffusive flux of salinity through Holocene formations to underlying aquifers. Fick’s second law can be used to simulate diffusion profiles shown in Figure 38, assuming a time span of 3000 years after deposition of the Thai Binh formation.

Chloride and effective diffusion coefficient for chloride in fine grained clay sediments (5.5 \(10^{-10}\) m\(^2\)/s; Apeldoorn et al. 2009). Lithology as well as natural gamma log in Q228 suggest fine grained sediments in the upper 90 m only intercalated by small silt and sand layers. The maximum salinity \(c_0\) was assumed 400 mmol/L, which is about \(\frac{3}{4}\) of modern sea water considering a partly refreshening of paleo-sea water. \(c_i\) represents the low saline Pleistocene pore water. Fick’s second law can be integrated for the boundary conditions:

\[
c(x,t) = c_i, \quad \text{for } x>0, t=0 \quad \text{and}
\]

\[
c(x,t) = c_0, \quad \text{for } x = 0, t > 0
\]

The solution of Fick’s second law for these boundary conditions is (Apeldoorn et al. 2009):

\[
c(x,t) = c_i + (c_0 - c_i) \text{erfc} \left( \frac{x}{\sqrt{4D_e t}} \right)
\]

This equation has been used to model vertical diffusion of chloride from saline Holocene sediments into Pleistocene aquifer, using variable effective porosities \((n_e)\) and, thus, effective diffusion coefficient \((D_e)\):

\[
c_0 = 400 \text{ mmol/L}; \quad c_i = 0.4 \text{ mmol/L}
\]

\[
D_e = D_f \times n_e; \quad D_f = 1.1 \times 10^{-9} \text{ m}^2/\text{s},
\]

\[
n_e = 0.2 - 0.4; \quad t = 3000 \text{ a}
\]

The shape and fit of the modeled diffusion curves (Figure 40) confirms that primarily high-saline pore fillings in Holocene formations can explain the observed salinity of underlying aquifers with vertical diffusion as major transport process. The best fit to measured pore water salinities is reached with \(D_e 2.2 \times 10^{-10} \text{ m}^2/\text{s}\) based a quite small \(n_e\) of 0.2.

Figure 40: Molar Cl content of pore water (orange) in Q228 plotted against simulated diffusion profiles (dashed lines with indicated \(D_e\)) and TDS (grey line, bottom x-axis) calculated from formation conductivity data.
The attempt to calculate TDS in pore water based on formation conductivity data and the linear corrections stated in Figure 37 (right) and Figure 39 is plotted in Figure 40 in grey color for location Q228. The resulting pore water salinity profile has to taken with care in the Holocene clay formations, due to lacking pore water data for verification. Hence, the analytic diffusion model helps to understand and quantify salinization processes in Nam Dinh as a basis for future numerical modeling of salinity intrusion processes.

4.3.3 Stable and Radiogenic Isotopes

Composition of stable water isotopes $\delta^2$H and $\delta^{18}$O have been analysed to provide information on fractionation processes taking place during groundwater genesis, mixing and movement. The isotopic data measured during Mai 2010 are documented in Annex 9.

The source of stable isotopic composition is given by precipitation data from Ha Noi station, believed to be representative for the RRD which have not undergone extensive evaporation. Dr. Dang Duc N. (INST-VAEC, written communic.) has reported a local meteoric waterline (LMWL, $\delta^2$H = 8.27x$\delta^{18}$O+14.52) based on monthly isotopic monitoring 2004-2009, comparable to earlier published LMWL based on data from 2002 to 2007 ($\delta^2$H = 8.3x$\delta^{18}$O+13.5, LARSEN et al. 2008). Time series of the annual distribution of $\delta^{18}$O in Hanoi precipitation shows an enrichment of $\delta^{18}$O in the dry season from October to May (0‰ and -4‰) and depletion during the rainy season with $\delta^{18}$O between -8‰ and -14‰ (LARSEN et al. 2008). This is caused by seasonal temperature oscillations as well as different rain catchment areas during winter/spring and summer rainy season.

Own surface water data from Day and Ninh Co River shows $\delta^{18}$O values (~ -8‰). They are in coincidence with published data from the Red River during dry season (LARSEN et al. 2008).

![Figure 41: Measured $\delta^2$H versus $\delta^{18}$O in surface and groundwater in Mai 2010. Dashed line represents the local MWL from Hanoi meteoric waters (LARSEN et al. 2008).](image1)

![Figure 42: Chloride versus $\delta^{18}$O concentrations in surface and groundwater in Mai 2010. Dotted line represents salinity mixing fresh line.](image2)
and plot near the local MWL (Figure 41). $\delta^{2}H/\delta^{18}O$ ratios in sampled shallow Holocene groundwater are depleted in $\delta^{18}O$ and plot along a trend with a lower slope than the MWL (dotted line in Figure 41). This trend is interpreted here not to represent fractionation due to evaporation but more likely a mixing line of fresh groundwater with seawater. The shallow coastal station Q111 marks the end member of the mixing line with $\delta^{2}H$ and $\delta^{18}O$ values close to the Standard Mean Ocean Water (SMOW). Q111 reflects recent marine salinization, however, other samples plotting on this line suggest increasing influence of paleo-seawater, taking the presumed origin of salinity in connate Holocene pore waters (see previous subchapter) into account. Consequently, in a plot of chloride versus $\delta^{18}O$ concentrations high saline Na-Cl dominated groundwaters from Holocene as well as Pleistocene aquifers align along a trend line, while fresh groundwater and surface water is scattered with low Cl and low $\delta^{18}O$ values (Figure 42).

The stable isotope composition in Pleistocene and Neogene groundwater shows two trends with one group plotting along the local MWL indicating ground water of meteoric origin. Furthermore, few data are depleted in $\delta^{18}O$ and strongly depleted in $\delta^{2}H$ (Figure 41). The isotopic depletion reflects recharge water precipitated at higher elevations, moreover the the strong depletion of $\delta^{2}H$ relative to $\delta^{18}O$ indicate additional fractionation processes due to water rock interaction. Depth and location of the sampling sites along faults may suggest influence of geothermal fluids, but this still needs to be clarified in further studies. Triassic formation water ($t_1$, $t_2$) plot close to the local MWL also representing meteoric groundwater, possibly in the extended Triassic limestone chains in neighbouring Nin Binh province.

**Tritium ($^3H$)** as a short-lived radioactive isotope of hydrogen has a half-life of 12.32 years (decay constant $\lambda = 0.0558/a$). Tritium forms naturally in the upper atmosphere, but during the 1950s and early 1960s, global atmospheric testing of nuclear weapons raised the atmospheric concentrations of tritium hundreds of times. After the early 1960s, tritium concentrations in the atmosphere have decreased and are approaching natural levels nowadays. Without $^3$He data or longer $^3H$-time series, tritium cannot be used to quantitatively date ground water, but to qualitatively determine if ground water is modern (less than about 50 years in age) or pre-modern (older than about 50 years in age). Low tritium values are also difficult to interpret because of seasonal variations of tritium input in precipitations. Tritium is expressed in tritium unit (TU), representing $10^{-18}$ mol/mol H and 0.118 Bq $^3H/L H_2O$.

Tritium has been measured in surface water, shallow and Triassic groundwater to confirm

![Figure 43: Depth profile of tritium ($^3H$) measured in river and shallow groundwater. Note that standard deviation of analysis (1σ) is ±0.2 in high TU up to ±0.4 in low TU data.](image)
or exclude portions of modern water (data see annex). The tritium activity in the precipitation collected in Ha Noi station is 3.27 (±1.41) TU and in water from the Hanoi Red River station is 3.94 ± 1.39 TU as monitored monthly since 2002 (reported by Dr. Dang Duc N., INST-VAEC). Measured tritium concentrations in Nam Dinh river water correspond with this level, whereas tritium seems to decrease continuously with depth in shallow ground water until it reaches levels within the standard deviation (Figure 43). Thus, the groundwater from the Vin Phuc and Triassic formations are believed to be older than 50 years. The low but still significant tritium content in Holocene data have been detected in Q108 and Q228, further interpretation is difficult when lacking ³He data and a dense depth profile to identify the “bomb peak”. Previous ³H/³He dating provides apparent vertical groundwater velocity of 0.5 m/a in Holocene sands of the RRD (POSTMA et al. 2007). Own calculation of vertical groundwater velocities has been based on coupled tritium data in stations Q108 (3.13 TU in 10m bgl; 1.74 TU in 45 m bgl) and Q228 (3.03 TU in 41m bgl; 0.73 TU in 65 m bgl), based on the decay equation \( \ln(\frac{3H}{3H_0}) = -\lambda \times t \) (APPELO et al. 2009) assuming simple advective transport. This results to quite high vertical apparent velocities of 0.9 m/a in Q228 and even 3.3 m/a in Q108. These values would be even higher when integrating diffusive and dispersive tritium transport processes into the calculation. Therefore, the occurrence of tritium in about 50 m bgl, especially in the old national monitoring site Q108, must be explained by insufficient well construction possibly opening new vertical pathways for modern groundwater.

**Carbon-14 (¹⁴C)** is the radioactive isotope of carbon with a half-life of 5,730 years (\( \lambda = 1.21 \times 10^{-4}/a \)). Like tritium, ¹⁴C is produced in the upper atmosphere and thus occurs naturally. Atmospheric carbon-14 concentrations were elevated by as much as 20 percent by the testing of nuclear weapons in the 1950s and 1960s (CHRISTENSON et al. 2006). It must be considered that in carbonate containing aquifers, ¹⁴C in ground water is diluted by reactions

![Figure 44: Ca/Mg ratio versus pH indicating high-Mg and low-Mg carbonate dissolution and high Mg due to mixing with sea water.](image)

![Figure 45: Depth profile of ¹⁴C activities measured in deeper groundwater samples. Standard deviation (1σ) ±1.1 to ±4.1.](image)
that introduce nonradioactive $^{12}$C into groundwater, which results in apparent $^{14}$C groundwater ages that are too old. The $^{14}$C activity is expressed as percent carbon in a “modern” pre-bomb testing atmosphere (pmc). Carbonate dissolution in closed systems lead to dilution of TIC by “dead” carbon from old carbonates and, thus, lower pmc.

Only samples with expected higher groundwater ages have been analysed for $^{14}$C in the study area. Under local circumstances, analysis of $^{13}$C and therefore correction of $^{14}$C data was not possible. Figure 44 sheds light on occurring carbonate dissolution processes in the study area. A pH about 8 and low molar Ca/Mg ratio in the $t_2$ groundwater suggest ongoing dissolution of high Mg calcite in a closed system with high partial CO$_2$-pressure, leading to an enrichment of dead carbon unable to escape by gas exchange. The portion of dead carbon in these closed environments can reach up to 50 % of the TIC (APPELO et al. 2009 ). After infiltration into qp and $n$ sediments continuous High-Ca carbonate dissolution results in increasing molar Ca/Mg ratio and decreasing pH. This general trend reaches its end members in the “brackish” qp and $n$ groundwater in W Nam Dinh. Note that high-Mg in Holocene units is due to increasing influence of (paleo-)sea water with molar ratio Mg/Ca <0.2 (dashed circle in Figure 44).

Figure 45 provides a clear general trend of decreasing $^{14}$C activities with increasing depth. High $^{14}$C in Q92 (75 pmc) suggests a high ratio of modern groundwater contributing to the

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>$^{14}$C (pmc) ±σ</th>
<th>$^{14}$C age (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q221n</td>
<td>21.6 ± 2.2</td>
<td>11300</td>
</tr>
<tr>
<td>Q221a</td>
<td>41.6 ± 1.7</td>
<td>5900</td>
</tr>
<tr>
<td>Q222b</td>
<td>28.3 ± 2.5</td>
<td>9100</td>
</tr>
<tr>
<td>Q223n</td>
<td>14.7 ± 3.2</td>
<td>14500</td>
</tr>
<tr>
<td>Q224a</td>
<td>28 ± 2.2</td>
<td>9200</td>
</tr>
<tr>
<td>Q225a</td>
<td>23.3 ± 3.2</td>
<td>9700</td>
</tr>
<tr>
<td>Q226n</td>
<td>16.5 ± 3.1</td>
<td>13500</td>
</tr>
<tr>
<td>Q226a</td>
<td>21.8 ± 2.2</td>
<td>10200</td>
</tr>
<tr>
<td>Q227a</td>
<td>15.8 ± 3.6</td>
<td>12900</td>
</tr>
<tr>
<td>Q228a</td>
<td>18.9 ± 3.5</td>
<td>11400</td>
</tr>
<tr>
<td>Q229n</td>
<td>16.7 ± 4.1</td>
<td>12400</td>
</tr>
<tr>
<td>Q229a</td>
<td>53.1 ± 1.6</td>
<td>2900</td>
</tr>
<tr>
<td>Q108b</td>
<td>51.1 ± 1.4</td>
<td>3300</td>
</tr>
<tr>
<td>Q109b</td>
<td>30.8 ± 2</td>
<td>7400</td>
</tr>
<tr>
<td>Q109a</td>
<td>19.2 ± 3.7</td>
<td>11300</td>
</tr>
<tr>
<td>Q110a</td>
<td>36.2 ± 1.8</td>
<td>6000</td>
</tr>
<tr>
<td>Q220T</td>
<td>47.8 ± 1.7</td>
<td>3700</td>
</tr>
<tr>
<td>Q92a</td>
<td>54.1 ± 2.5</td>
<td>850</td>
</tr>
<tr>
<td>Q92</td>
<td>74.6 ± 1.1</td>
<td>1100</td>
</tr>
</tbody>
</table>

Figure 46: Depth profile of GW ages based on $^{14}$C ($t_1$, $t_2$, $n$, qp; corrected) and tritium (qh1, qh2) measurements. Dashed line mark an estimated vertical recharge rate (italic), assuming a closed hydraulic system.
4. Integrating Results into a Conceptual Model

Pleistocene aquifer below the Dao River Bed, due to a high hydraulic gradient from the catchment area in Ninh Binh to the RRD. The initial activity ($A_0$) of $^{14}$C for conversion of pmc into $^{14}$C ages was suggested to be 85 pmc (Dr. Dang Duc N., INST-VAEC) due to carbonate dissolution in groundwater of the RRD. This “rule of thumb” was modified based on the observations stated above to $A_0$ 60 pmc for $t_2$ karst groundwater and $A_0$ 75 pmc for qp groundwater in case of pH >7.3 and aligned on the low Mg-carbonate dissolution trend line.

Based on these assumptions $^{14}$C-ages have been calculated (Table 7) and should be understood as conservative estimations. Nevertheless, they provide a clear spatial relationship when plotted into contour maps for qp and n units (Figure 47). Distribution of $^{14}$C ages reflect in both maps the inflow from the Triassic units in the W as well as from the NW in case of n unit. Groundwater ages in the n unit increases eastward up to maximum 14500 a. However, in case of qp groundwater maximum ages are identified in the central part of the

![Figure 47: Contour plot showing calculated $^{14}$C ages (a) in qp (top) and n (bottom) unit interpolated using natural neighbour method. $^{14}$C ages for $t_1$ and $t_2$ data have been applied in both plots as boundary conditions assuming a hydraulic connection as demonstrated in previous subchapters.](image-url)
4. Integrating Results into a Conceptual Model

Fresh water area (Q227, 12500 a). It is not surprising that pore water in n unit is generally older than in qp. However, in the central part of the fresh water lens, relatively young n groundwater underlies older qp groundwater, which is demonstrated in site Q109 with qp groundwater about 4000 a older than in n unit (Table 7). This is consistent with higher hydraulic heads observed in n relative to qp unit in that area. Therefore, a direct recharge of n unit from Triassic hard rock aquifers and/or water-bearing fault zones as well as the vertical upward directed groundwater flow from n to qp aquifer is evident.

Finally, a depth profile (see Figure 46) of calculated as well as estimated groundwater ages based on $^{14}$C and $^3$H quantifies the qualitative picture indicated by Figure 45. Note that data from Red River area (Q221, Q222, Q223, Q224) have been excluded in order visualize a closed hydraulic system dominated by inflow from triassic aquifers. The groundwater ages of Triassic, qp and n aquifers are aligned on two trend lines representing slopes of ~4 mm/a and ~15 mm/a. This might be taken as vertical recharge rates even when quite low considering a humid climate and high precipitation rates. However, this confirms the dominant horizontal recharge of qp and n units from Triassic aquifers and a relatively low vertical recharge due to overlying low permeable aquicludes. Please note the higher vertical recharge rate during sea level low stand (>10,000 BP) comparing to sea level high stand (<10,000 BP see chapter 4.1.1). Outliers are possibly originated in their close vicinity to neighbouring hard rock aquifers (Q109, Q108) or infiltrating surface water (Q92).

4.3.4 Solutes Affecting Drinking Water Quality

The previous subchapters discussed the major and isotopic composition respective origin and genesis of groundwater in Nam Dinh. In this context, the limitation for groundwater usage due to high salinity became evident (chapter 4.3.2). Complementary, this subchapter focuses on solutes potentially effecting groundwater quality even in low saline areas, where it is extensively used for consumption.

During the last two decades the transition metal arsenic (As) in groundwater has achieved special awareness in the scientific community as well as the public. The occurrence of high dissolved As levels mobilized from geogene sources in pore water has evolved to be a global issue, complicating groundwater usage worldwide (e.g., Ravenscroft et al. 2009; Welch et al. 2003). In particular shallow aquifers in relatively young river plains and delta systems are affected due to their high content of immature and organic rich sediments. In these environments, main drivers controlling As release and retention are biogeochemical redox and ion exchange processes, and As transport is governed by local hydraulic regimes. However, infiltration of organic rich waste water and pumping activities potentially accelerate As mobilisation and transfer. Well-known examples in South East Asia are the Ganges-Brahmaputra River plain and Bengal Delta, the Mekong Delta and the RRD.

A number of recent international scientific publications provide detailed case studies in order to understand the complex mobilisation and transport mechanisms of arsenic in RRD, e.g., Berg et al. 2008; Eiche et al. 2008; Giger et al. 2003; Jessen et al. 2008; Larsen et al.
Dissolved As in Nam Dinh groundwater reach concentrations up to 160 µg/L increasing 16fold the international and national drinking water threshold (10 µg/L; MOH 2009; WHO 2008). High As concentrations mark a characteristic bell-shaped depth profile with maximum between 40 and 80 m depth, but still significant levels have been found down to 120 m bgl (Figure 46, top left). Herewith, the value of Q111 is considered as an outlier representing near sea-water composition including very high levels of trace elements such as As. Affected aquifers are mainly early Holocene (Hai Hung) and late Pleistocene units (Vin Phuc). The depth profile indicates the redox-sensitive character of As, resulting in high As(III) in depth with a predominating reducing environment, due to the consumption of electron donor such as dissolved oxygen and nitrate.

The redox-state of dissolved As (III, V) has not been analyzed in this study, however, the good correlation of As with other redox-sensitive parameters such as dissolved iron (Fe),

Figure 48: Depth profile of dissolved As (top, left) and correlation between As and other parameter.
4. Integrating Results into a Conceptual Model

Manganese (Mn) and ammonia (NH₄) confirm the mobilisation and desorption of reduced As(III) in this picture (Figure 46, bottom). Since a significant As fraction is commonly bound to amorphous and crystalline Fe-oxides and –oxihydroxides, Fe(III) reduction and Fe(II)-dissolution can be one major mobilization process, commonly parallel to mobilization, demobilization and competitive desorption processes. Microbial degradation of organic matter in the aquifer is regarded as the main driver for biogeochemical redox-processes and, thus, the mobilisation of As. This is demonstrated in Nam Dinh groundwater chemistry by a good correlation of As with the microbial degradation products NH₄ and total dissolved organic carbon (TOC, Figure 46, top right).

Vertical as well as horizontal redox-zonation in young immature sedimentary aquifers has been reported to be complex due to hydraulic, sedimentary and resulting hydrogeochemical frame conditions and, thus, spatial distribution of dissolved As in groundwater extremely changes even in a small scale (e.g., Wagner et al. 2005). Consequently, high dissolved levels of redox-sensitive parameter in Nam Dinh’s Holocene formations distribute scattered (data not shown). However, this is not the case for the qp unit, since even a coarse sampling density reveals a distinct spatial relationship with high dissolved As levels below the Red River area and low As in the fresh pore water in centre and W of Nam Dinh (see Figure 49). Similar spatial relationship can be observed with other redox-sensitive solutes, such as Fe and NH₄ (not shown). Obviously, anoxic redox conditions dominates the hydrogeochemical environment in qp an n units of the Red River area, whereas possibly suboxic redox conditions occur in S and W Nam Dinh even when sediments are believed to have similar age and composition. It seems that the specific hydraulic regime in that area has stabilized a relatively high redox-regime within suboxic levels, inhibiting mobilisation of significant As. Furthermore, the predominant eastward hydraulic gradient during tens of thousands years may have accelerated microbial degradation processes and flushed the resulting pore water.
containing mobilized As, Fe, NH₄ and other redox-sensitive solutes. Considering an average groundwater age of 10,000 a in the centre of Nam Dinh (see Figure 45), pore volumes of Pleistocene formations have been flushed ~20 times (qp₂) or ~50 times (qp₁), respectively.

Even without information about the local groundwater quality, local people have an idea about the Fe content in their water due to the metallic taste and digestion problems when consuming high-Fe water. Thus, some households representing elevated income and education level, installed simple sand filters systems, treating ground water extracted from own tube well water for drinking and cooking purpose (see Figure 50). This sand filter technique has proven not only to remove Fe(II) from the water due to oxidation and precipitation, but also As due to coprecipitation and adsorption processes. The easily observable removal of iron from the pumped water makes the effect of a sand filter immediately recognizable even to people who are not aware of the arsenic problem (BERG et al. 2006; TOBIAS et al. 2011). Nevertheless, these sand filter types are much less effective in low-Fe and high-As water or high PO₄ water. In any case maintenance of the sand filters efficiency and testing of their efficiency should be carried out continuously.

So far, no symptoms of chronic As poisoning have been reported from Nam Dinh or other provinces in the RRD, possibly because of the relatively short-term usage of high As groundwater in less than 10 years (BERG et al. 2007). However, increased groundwater pumping is considered to accelerate As mobilization and transfer processes (STUTE et al. 2007) and long-term exploitation may result in a drawdown of dissolved As into deeper aquifers (WINKEL et al. 2011). Therefore, future systematic monitoring of As levels in groundwater in Nam Dinh is essential and dissemination of remediation and simple testing methods as well as technical support is strongly recommended.

Earlier sections already demonstrated, that major composition negatively affects groundwater quality, comprising redox-sensitive solutes mobilized in a reducing environment (As, Fe, Mn, NH₄) as well as due to (paleo-)sea water salinization (Cl). Further substances of certain concern for consumption are borate and bromate (BO₂, BrO₃).

The oxoanions of boron and bromine generally occur only in traces (<1 mg/L) in fresh groundwater. Increased dissolved levels indicate infiltrating industrial and domestic waste water. In the study area high dissolved levels in Holocene pore water reaching concentrations up to standard sea water (BO₂ ~10 mg/L, BrO₃ ~50 mg/L, Ba ) are still significant (> 1mg/L) in Pleistocene units in N and E Nam Dinh. Since, high bromate as well as boron levels are associated with high Cl pore water, they represent a good tracer for influencing (paleo-)sea water (data not shown). Boron is suspected to have negative effects to male reproducibility and bromate to be cancerogen if toxic amounts are consumed continuously (WHO 2008). Therefore, WHO 2008 suggests provisory thresholds for drinking water of maximum 0.5 mg/L B and 0.01 mg/L BrO₃. The Vietnamese drinking water guideline state a threshold of 0.3 mg/L B and does not include BrO₃ (MOH 2009). Note that even in the deeper qp and n pore waters the Red River area contain dissolved BrO₃ of several mg/L (max. 8.6 mg Br/L, corresponding to 13.8 mg BrO₃/L). These solutes need to be considered when developing treatment methods for brackish groundwater in N and E Nam Dinh.
The **nitric compounds** in Nam Dinh groundwater deserve some final notes in this subchapter. The occurrence of high ammonia (NH$_4$) has already been stated above, in case of nitrite (NO$_2$) and nitrate (NO$_3$) the results delivered from different laboratories are misleading. Origin of N-compounds in deeper aquifers such as the qp and n units are natural organic matter in the immature sediments, less likely from infiltrating waste water or fertilizer. Microbial degradation of the organic matter results in mineralization and release of anorganic N-compounds in oxidized (NO$_3$) or reduced (NH$_4$) form, generally depending on the predominating redox-conditions. NO$_2$ represents a transition species between the reduced and the oxidized N-species, and generally occurs in natural groundwater in dissolved levels <1mg/L. However, NO$_2$ deserves special regard due to its high toxicity, especially for bottle-fed infants (WHO 2008). The BGR laboratory reported some remarkably high nitrite and nitrate levels of several mg/L in the deeper qp and even n aquifer. However, these values are considered to be a result of NH$_4$-oxidation during the transport to Hannover, Germany, favored by an interrupted cooling chain. The VAST laboratory determined NO$_2$ of max 0.1 mg/L and NO$_3$ <2 mg/L only few days after sampling. According to VAST analysis, NH$_4$ is the dominant species in low saline pore water of qp and n unit in S Nam Dinh, indicating generally a predominant anoxic environment. Only in the center and S Nam Dinh (Q109, Q227, Q228, and Q229) nitrate and ammonia are both in low but significant levels with a molar ration of 0.1-0.5 NO$_3$/NH$_4$, indicating a suboxic environment just below +300 mV (Eh$_{ph7}$) and nitrate reduction as the dominant redox-process.

It is evident that the determination of N-compounds must take place directly after sampling or samples should be treated accordingly to prevent ongoing microbial activity. This should be kept in mind, since N-compounds are of special environmental concern and subject of any monitoring plan and water quality guideline. The Vietnamese drinking water guideline states maximum acceptable levels for NH$_4$ (3 mg/L), NO$_3$ (50 mg/L) and NO$_2$ (1 mg/L). Facing much higher dissolved NH$_4$ in drinking water, please note that NH$_4$ in drinking-water is considered not to have immediate health relevance, and therefore no health-based guideline value is proposed by the WHO. However, NH$_4$-oxidation during water storage may result in high NO$_2$ waters and should not be used for feeding infants.
**Recommendations, chapter 4.3:**

- Origin of fresh water inflow to qp and n units need to be confirmed, \( t_1, t_2 \) or water-bearing faults?

- Future water sampling campaigns should concentrate more on possible Triassic aquifer \((t_1, t_2)\) to identify their contribution to qp and n groundwater budget.

- Salinity in Monitoring wells and, thus, movement of 1g/L and 3g/L salinity boundaries need to be closely monitored.

- Application of Fick’s laws in order to model and understand diffusive transport from Holocene to Pleistocene aquifers.

- The valuable results from \(^{14}\)C and \(^2\)H/\(^{18}\)O isotopic studies should be extended and confirmed in future sampling campaigns, including \(^{13}\)C analysis correction of \(^{14}\)C activities.

- Simulation of carbonate dissolution and precipitation processes using geochemical reactive transport modelling can specify the assumed \(^{14}\)C \(A_0\) activities.

- In Red River area: ongoing monitoring of dissolved As in groundwater and dissemination of sand filter techniques for simple groundwater treatment (Fe, As removal) including the provision of technical support.

- Future water quality studies need to include microbial parameter (e.g., ecoli).
5 Conclusions with Respect to GWRA

5.1 Major Factors Controlling Hydrogeology of Nam Dinh area

In the beginning of this study, it was found that groundwater is rarely used in large parts of Nam Dinh due to high salinity and pollution. Nevertheless, in some areas in the center and S of Nam Dinh deep groundwater is extensively used. Thus, this study aims to facilitate responsible authorities to quantify this situation as a basis for future regulations for water management. Moreover, it claims to represent a fundament for further technical and scientific studies in that area.

Therefore, the preceding chapters established a comprehensive picture explaining the frame conditions and dominating mechanism leading to the specific hydrogeologic system observed in the subsurface of Nam Dinh (chapter 4). This culminates into water budget calculations and scenario analysis carried out by a numerical hydrogeological model (see this report, Part B). The present chapter summarizes the general findings and draws conclusions and implications with respect to a groundwater resources assessment (GWRA).

Due to its location at the Southern rim of the RRD, Nam Dinh has a specific geologic and hydrogeologic setting. Proterozoic horst in the NW of Nam Dinh is a major structural feature representing a hydraulic barrier between the Western Triassic hard rock aquifers and the eastern RRD. Southward of this barrier, the unconsolidated qp and semi-consolidated n aquifer receive significant recharge from Triassic t1 and t2 formations in West and NW of Nam Dinh and possibly also from water-bearing fault zones in the basement as suggested from hydrochemical and stable isotope data (chapter 4.3). The specific contribution of each of these sources has not been distinguished yet; however, the influx during several ten thousand years was sufficient to establish a low saline water lens in Pleistocene and Neogene formations of very high drinking water quality (Figure 51).

The higher permeable layers of the covering Holocene formations are not exploitable on a larger scale, due to insufficient yield and water quality. However, the predominantly low permeable strata inhibit intrusion of surface water and therefore salinization as well as pollution of deeper aquifers. A large portion of the Holocene fine grained sediments have accumulated in a marine environment and, thus, contain saline pore water representing the major source for salinization due to diffusive transport into deeper aquifers (chapter 4.3.2). Diffusion modelling for the time span of 3000 years confirms that high-saline Holocene pore waters as the major source and vertical diffusion as the major transport process is sufficient to explain elevated salinity in brackish qp and n pore waters East of Nam Dinh (Figure 51). In the West and Southwest of Nam Dinh, fresh and low saline pore water in qp and n aquifer only persist due to the continuous inflow of fresh water from the adjacent Triassic hard rock aquifers.
However, in SE, E and NE of Nam Dinh, the high saline pore water of marine origin still dominates the composition of groundwater in deeper aquifers. Moreover, the predominant reducing environment provides the frame for accelerating the mobilisation of redox-sensitive and potentially toxic substances, such as arsenic, ammonia, iron and manganese (chapter 4.3.4). Therefore, high yielding Pleistocene and Neogene aquifers in large areas of N, E and SE Nam Dinh, are considered not to be usable for drinking water supply without applying appropriate water treatment technologies. Special caution to groundwater use must be spend on the transition areas of fresh to brackish salinity (1 g/L to 3 g/L) where the water may be usable in terms of salinity, but contain toxic levels of redox-sensitive solutes such as arsenic, iron and ammonia.

Increasing extraction and usage of high quality Pleistocene groundwater in central and S Nam Dinh exceeded groundwater recharge since 1995 with huge impact on the natural geohydraulic system (chapter 4.2.2). A regional abstraction cone documents groundwater level drawdown of up to 0.6 m/a in Pleistocene as well as Neogene aquifer. In this area, the natural coastward directed groundwater flow has turned towards the centre of the abstraction cone with horizontal apparent velocities of up to 0.6 m/a (up to 0.2 m/a in n unit). This suggests the migration of brackish and higher saline groundwater from E Nam Dinh and offshore towards the area of fresh groundwater. Thus, the movement of the saline boundary should be focussed in future monitoring studies. The lack of recent and reliable groundwater extraction data is a crucial handicap for understanding the water budget in qp aquifer and its replenishment.

In this context, vertical groundwater flow from and to qp might be low but cannot be omitted. In sandy Holocene formations, an apparent vertical flow of 0.5 m/a has been reported (POSTMA et al. 2007). It has been demonstrated in this study that vertical flux in the shallow fine grained, clay dominated formations in Nam Dinh is much lower and governed by diffusion transport processes. Isotopic studies in Pleistocene and Neogene sediments suggest an apparent vertical flux of only 4 to 15 mm/a.

In the centre of the abstraction cone, an upward directed vertical groundwater flow between

![Figure 51: Conceptual cross section 5 (location Figure 18) demonstrates some major results of this study regarding pore water salinity and flux in Pleistocene and Neogene unit, summarized in this chapter. Colours represent fresh (blue), brackish (orange) and saline (red) pore water, italic figures indicate proposed 14C-age in years (a).](image-url)
5. Conclusions with Respect to GWRA

qp and n unit is suggested by $^{14}$C groundwater dating (chapter 4.3.3) as well as an upward geohydraulic gradient in this area (chapter 4.2.2, Figure 51). This gradient may result in an upwelling of 0.17 m/a based on a mean measured conductivity (slug test) and vertical anisotropy factor of 0.1. However, vertical conductivity data from undisturbed drilling cores and pump tests are necessary to quantify this upwelling further.

Aquifer properties have been quantified by using relatively simple and cost-effective methods. General obstacles were the lack of undisturbed drilling cores and long-term pump tests. However, the applied methods provide consistent horizontal conductivity data in high permeable strata. Moreover, time series analysis of hydraulic heads in confined aquifers was useful to calculate storativity properties from the aquifers elastic response to barometric and tidal fluctuations (chapter 4.2.1.2); a crucial parameter for water supply and water budget calculations. The storativity data underline the high relevance of the n aquifer for water supply in a 8fold higher storativity ($4 \times 10^{-4}$) as observed in qp ($6 \times 10^{-5}$), indicating the higher aquifer thickness as well as a higher pore water pressure in the Neogene formation. Again, this needs to be confirmed by long term pump tests.

Results of the numerical modeling (see this report, Part B) suggest that exploitation of the groundwater resources will not be reversible, as the demand for freshwater is way greater than the potential fresh groundwater recharge in the model area. With the current model settings a freshwater intake of about 8000 m³/d stands in contradiction of an extraction of more than 60,000 m³/d. Sustainable groundwater resource management is probably not possible any more. Thus, a change of the strategy of water withdrawal must be considered. A spatially distributed extraction as it is currently done will likely lead to a faster intake of saline water than a concentration of extraction of water at the northwestern boundary in specific depths of the aquifers.

5.2 Objectives for Future Technical and Scientific Studies

As demonstrated in preceding chapters, the presented study provides a new and consistent picture about the hydrogeologic system of Nam Dinh, which is crucial for local and regional groundwater management. Since new insights always raise new questions, further technical and scientific tasks listed below are suggested to improve the fundament on which water management decisions should be based.

Geological & Hydrogeological System Understanding

- Localization and identification of the hard rocks in the West and SW of Nam Dinh, especially the occurrence of T1 formation in the subsurface.
- Identification and localization of water bearing faults, to clarify their contribution to the groundwater budget in Nam Dinh area.
- Further observation of Q1 (Vin Phuc) formation to clarify its relevance for groundwater exploration, specifically its role for isolating deeper qp aquifer from shallow aquifers and representing locally/regionally a yielding aquifer.
5. Conclusions with Respect to GWRA

- Composition of Q₂ sediments is heterogeneous and, due to the focus of this study on the stratigraphic point of view, distribution and connection of high permeable and regional low permeable layers are still not well understood. Thus, a comprehensive reinterpretation of available archive drilling and well logging data is recommended.

- Origin of fresh water inflow to qp and n units need to be confirmed (t₁, t₂ or water bearing faults) and quantified.

- Collection and update of GW extraction data are crucial to assess and quantify the GW overexploitation in Nam Dinh.

Improving knowledge about aquifer characteristics

- Aquifer parameters regarding low permeable strata are still lacking, but are relevant to understand vertical hydraulic connection and flux.

- Long-term cluster and step draw-down pump tests are necessary to confirm aquifer parameters determined in this study. Pump test data must be corrected by barometric as well as tidal effects.

- A complex analysis of groundwater head fluctuation is recommended, with the aim to identify interfering effects of barometric, tidal and other origin and to determine BE in all wells despite of predominating external influences (e.g. GONTHIER 2007).

- Analyzing tidal effects with more advanced analytical models can improve accuracy of tidal derived aquifer parameter.

Monitoring of Groundwater Quantity & Quality

- The regional abstraction cone in Nam Dinh should be delineate in higher detail using local monitoring and household wells if screen depths are approximately known. Manually measurements in these sites twice per year can supplement data from the national monitoring network.

- Continuous and long-term groundwater monitoring is a crucial base for future groundwater management decisions.

- Future water quality sampling campaigns should focus more on Triassic aquifer (t₁, t₂) to identify their contribution to qp and n groundwater budget.

- Salinity in Monitoring wells and, thus, movement of 1 g/L and 3 g/L salinity boundaries need to be closely monitored.

- The presented results from ¹⁴C and D/H/O isotopic studies should be extended and confirmed in future sampling campaigns, including ¹³C analysis for correction of ¹⁴C activities.

- W Nam Dinh / Red River area: continuous monitoring of dissolved As in groundwater and dissemination of sand filter techniques for simple groundwater treatment (Fe, As removal), including the provision of technical support.

- Even when high observed nitrite levels are in doubt, they need to be confirmed by further field studies due to their negative health effects.
• Future water quality studies need to include microbial parameter (e.g., ecoli).

3D-structural and Numerical Modelling

• In order to serve as a planning tool for future water management decisions, the 3D structural and numerical model should be constantly actualized by new datasets and improved to reduce the gap between reality and modelling abstraction. It remains a political decision in order to provide the necessary resources in the future.

• One major step to improve model results would be the enlargement of the model area to the graben boundary in Ninh Binh. This is necessary to grasp the connections of graben border geology to the Neogene groundwater bodies and would clarify recharge assessment.

• It is especially necessary to estimate aquitard parameters and associated specific storage values for all hydrogeologic units.

• Model results would greatly improve when extraction from qp and n aquifers are further quantified, it is likely that with a further quantification scenario analysis in future become possible.

• The extension of the model to transport and density flow modelling would be a further step to understand the salinity-freshwater complex.
6 Recommendations for Groundwater Management

Increasing overexploitation and salinization of deeper unconsolidated aquifers in Nam Dinh raise the question about the replenishment of the deep fresh groundwater and the response in frame of new water management strategies. At least a large portion of the GW recharge originates from the Triassic hard rocks in Ninh Binh area in the W of Nam DInh. This demonstrates the trans-boundary behaviour of water resources, since the neighbouring catchment area in Ninh Binh province need to be integrated in GW balance calculations for Nam Dinh province. It is strongly recommended that decision makers provide funding for further technical studies (chapter 5.2), since groundwater extraction must not exceed the amount of recharge to prevent mining of fresh groundwater.

Figure 52 visualize a cost–benefit analysis of a groundwater resources assessment (GWRA), consisting of (1st) continuously integrating of available data in a groundwater information system (GWIS), (2nd) the design of the conceptual hydrogeological understanding and (3rd) analytical & numerical modelling and scenario analysis. Note that the quality of the achieved goal must depend on available resources. Therefore, prior to any technical GWRA, the responsible authorities must clearly define their requirements and mobilize the necessary resources to reach the envisaged goal.

However, the current exploitation in Nam Dinh already exceeded the aquifer capacities of recharge with fresh water since 1995 and, thus, the responsible authorities must respond in form of new management and mitigation strategies aiming at more sustainable solutions. Thus, a close connection between water policy, science and engineering, and a strong cooperation between different groundwater users such as water supply companies, agriculture, aquaculture and other industries as well as domestic households is crucial. (Ground)Water Resources can only be managed successful in frame of a transboundary approach, integrating all relevant institutions and stakeholder (Integrated Water Resources Management).

The list below provides practical challenges in order to manage overexploitation and |

Figure 52: Cost–benefit analysis about the relationship of the accuracy a groundwater resources assessment (GWRA) and the invested resources. Prior to GWRA, responsible authorities must define required improvement of the current status and mobilize the necessary resources.
salinization, potentially leading towards a more sustainable groundwater usage in Nam Dinh province.

- **Controlling extraction**: Continuously updated information about the groundwater extraction status is crucial for managing groundwater resources. This comprises not only governmental (communal) water extraction, but also for industrial, agro- and aquaculture purpose as well as an assessment about the decentralized extraction from private households.
  
  - Well registration and extraction licensing measures must be realized consequently and transparently.
  
  - Central water supply coverage should be extended continuously to reduce uncontrolled water extraction.

- **Reducing extraction**: Availability of high quality groundwater is limited and a national reserve and, therefore, should be kept for drinking water purposes. It should be used for domestic drinking water supply only and whenever possible replaced by surface water usage. Necessary actions:
  
  - Identification of sources for groundwater loss or misuse, together with the design and approval of mitigation strategies. Leaking wells, pipes, tubes and taps are common causes for wasting groundwater.
  
  - Identification of alternatives for groundwater usage with lower priority, such as (i.) application of saline tolerant crops in agriculture, and (ii.) treatment and usage of surface water for industry, aqua- and agriculture.

- **Increasing recharge**: Potential areas need to identified, where adequate technologies can be applied, in order to increase the groundwater recharge with artificially infiltrated precipitation and low saline surface water. Prior feasibility studies are needed to assess carefully the long-term risks for the subsurface environment as well as to develop appropriate geotechnical and monitoring strategies.

- **Optimizing extraction**: Salinization of remaining fresh groundwater can be minimized by applying appropriate exploitation strategies with focus on the W Nam Dinh. This can only be achieved by having detailed knowledge about the local subsurface structure and their hydraulic characteristics.

- **Conjunctive usage**: Mixing of high quality water with poorer quality water may extend the available amount of water with still acceptable quality for water supply. This should be understood as an intermediate action while realizing the recommendations above.

- **Groundwater monitoring plan**: A monitoring plan need to be established including funding for continuous monitoring of groundwater quality and quantity. Data collection and analysis must be carried out by technical experts with sufficient hydrogeological background. The current national & provincial monitoring efforts must be synchronized and data exchange improved.
7 Extended Summary

An extended Summary of this report is provided in frame of a comprehensive “Executive Summary about Major Conclusions and Recommendations for Water Management”. It is published in frame of a separate document in Vietnamese and English language, aiming for decision makers on a political level. Kindly refer to IGPVN office for further information.
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