Groundwater monitoring and modelling from an archaeological perspective: possibilities and challenges

Hans de Beer[1] and Henning Matthiesen[2]

[1] Geological Survey of Norway (NGU), 7491 Trondheim, Norway.
[2]National Museum of Denmark, Copenhagen, Denmark.
E-mail: hans.debeer@ngu.no

Since 2002, an intensive monitoring scheme at the World Heritage site of Bryggen in Bergen, western Norway, has shown damaging settling rates caused by deterioration of underlying cultural deposits. Monitoring focuses on both chemistry and quantity of groundwater and soil moisture content in the saturated and unsaturated zone. Continuous logging of piezometric head, oxygen and soil moisture content and chemical analyses of water and soil samples are key elements. The monitoring includes registration of movement rates for buildings and soil surface, field measurements and archaeological recording in small excavations, as well as studies of archaeological and modern materials in the subsoil. The results have given good insight into the preservation conditions, with focus on deterioration rates. Groundwater monitoring and chemical analyses reveal a dynamic flow regime under the thick, organic cultural deposits of the site. The flow regime is controlled by interaction of tidal fluctuations, urban drainage systems, natural and urban stratigraphy and bedrock hydraulic features. The documented preservation conditions within the cultural deposits as well as oxygen and moisture-content fluctuations in the unsaturated zone have a significant correlation with the different groundwater flow dynamics found throughout the site. It is demonstrated that groundwater and soil-moisture monitoring, combined with 3D transient modelling are potentially effective routines to improve the understanding of preservation conditions in complex archaeological surroundings and, therefore, protection of archaeological deposits in situ.

de Beer, H. and Matthiesen, H. (2008) Groundwater monitoring and modelling from an archaeological perspective: possibilities and challenges. *In* Slagstad, T. (ed.) *Geology for Society*, Geological Survey of Norway Special Publication, **11**, pp. 67–81.

Introduction

Preservation conditions of archaeological remains preserved in situ are dependent on both the natural environment and changes to this environment caused by urban development, agriculture or climate changes (Holden et al. 2006). Most variables influencing the preservation conditions are closely related to the presence or absence of groundwater. Absence of water leads to increased flux of oxygen into the deposits and increased deterioration of archaeological materials. Therefore, to better understand the preservation conditions and eventually design measures to protect archaeological deposits, it is necessary for any archaeological site to be placed within its wider natural environment, and to thoroughly understand the natural hydrogeological balance and possible changes that are being forced upon it by nature or human activities.

In situ preservation is often preferred to excavation as a sensible way to manage non-renewable archaeological resources (Valetta Treaty 1992). The idea is to leave some undisturbed archaeological remains as research material for future generations of archaeologists, who will probably have better methods and who will certainly ask different questions than today. Also, constraints on museum space, and conservation and curation costs, limit excavation. In situ preservation is, however, only a viable strategy if the archaeological deposits are lying in a steady, balanced environment, with no or only insignificant decay going on (Corfield et al. 1998, Nixon 2004). As groundwater is a major factor, monitoring of the piezometric head and chemical analysis of groundwater and soil pore water are included in many monitoring projects of archaeological deposits. However, only few attempts exist to combine dynamic hydrogeological and geochemical data in an integral interpretation focused on preservation conditions. A first attempt to compare the chemical analyses from Bryggen in Bergen, western Norway, with monitoring data from Parliament Street in York, Tower of London, and leachate from landfill sites was made by Matthiesen (2008).

Monitoring of the preservation conditions in the archaeological deposits at the World Heritage Site Bryggen in Bergen has been ongoing since 2002. The monitoring covers both the saturated and unsaturated zone and includes detailed chemical analysis of water and soil samples, continuous logging of piezometric head, oxygen and soil moisture content, measurements of movement rates for buildings and soil surface (Jensen et al. 2004), field measurements in test pits, as well as studies of archaeological material and modern samples left in the soil for a few years. It has been found that preservation conditions within the 0.02 km^2 study area vary considerably, from excellent to very poor preservation conditions, as well as intermediate zones with less ideal preservation conditions (Matthiesen et al. 2007).

This paper will focus on the underlying causes of these conditions, by linking integrated hydrological investigations such as high-resolution groundwater monitoring, modelling and chemical analysis to archaeological investigations. We will test the following hypotheses:

H1. A combined hydrological and archaeological approach leads to a more fundamental understanding and thus improved protection of the archaeological site in situ.

H2. A combined hydrological and archaeological approach improves identification of archaeological deposits at risk.

Site description

History

Bryggen in Bergen, with its traditional timber buildings, is one of the oldest trading ports in northern Europe, and one of the Hanseatic Leagues' four overseas offices. The current buildings are from 1702, but have a pre-Hanseatic building structure dating back to the 11th century (Figure 1). A historical map showing important (former) hydrogeological features such as drainage patterns, former coastline and catchment areas during the Middle Ages is shown in Figure 2.

Figure 1. Traditional timber buildings of Bryggen, interconnected in long rows with narrow straits in-between.

In 1955, a large fire destroyed about a third of Bryggen's buildings, on the western side of the study area. Extensive archaeological excavations took place in the period from 1955 to 1968 by A.E. Herteig (Herteig 1985). In 1979, Bryggen was included in the World Heritage list based on the selection criterion *"to bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared"* (Unesco 2008). The total system comprising the World Heritage Site Bryggen, including underground archaeological remains plus 61 buildings, i.e., from the underlying bedrock to the rooftops, is to be considered a single cultural monument.

After Herteig's archaeological excavations were completed in 1968, a hotel with underground parking lot was constructed in 1979 at the former excavation area, west of the remaining part of Bryggen.

Low phreatic levels and increased flux of oxygen in the

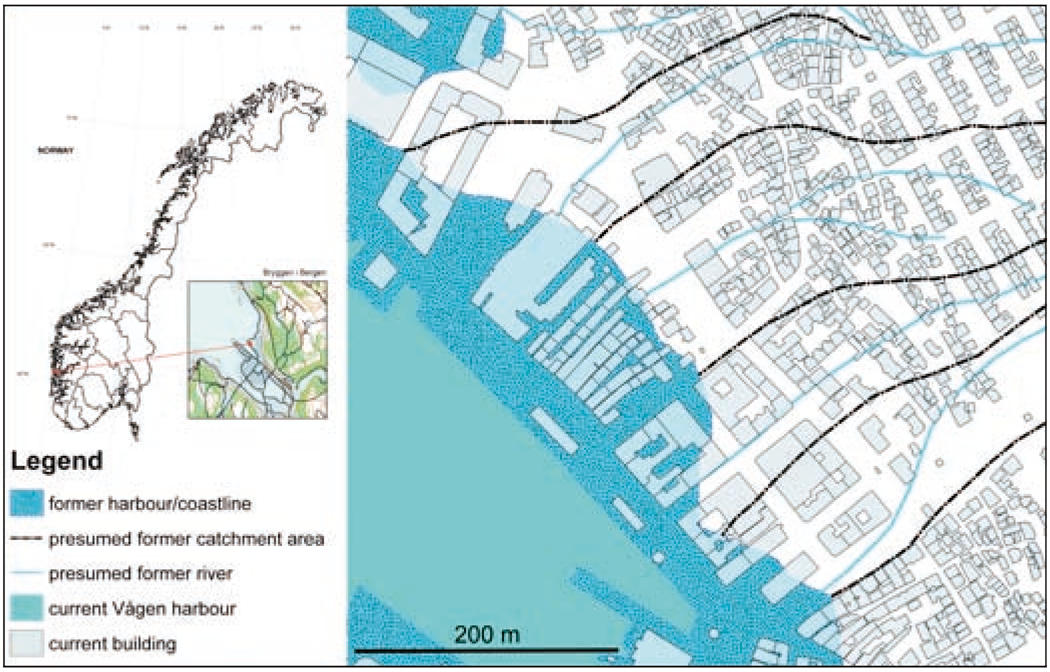

Figure 2. Index map and historic map showing important hydrogeological features such as former natural drainage patterns, coastline and catchment areas during the Middle Ages (modified after Department of History, University of Bergen).

subsurface, leading to decomposition of organic material and settling, currently threaten World Heritage Site Bryggen. A large restoration project is running from 2001 to 2021, covering all the buildings and their foundations. The strategic project aims to bring Bryggen to a state of repair that is in accordance with the status as a World Heritage Site, and where only regular maintenance is necessary. More details on the history of Bryggen are given in Christensson et al. (2004).

Archaeology

Below the buildings lie cultural deposits covering the entire span of Bryggen's history. The excavations in 1955–1968 revealed an excellent state of preservation and a huge amount of information in the deposits (Herteig 1969). It has been, and will be, a of great importance to understand the different ways in which the cultural layers were deposited, and to interpret the varying relationships between layers and constructions (Myrvoll et al. 1983, Christensson et al. 2004). At Bryggen, the cultural deposits with their 'cargo' of constructions and artefacts add up to a thickness exceeding 8 m in places, with 10 or more separate building phases one on top of the other. A 'typical' sequence consists of layers with high organic content interspersed with fire-layers, the latter being the remains of many fires that struck Bergen in medieval and later times. The deposits are highly organic, with loss on ignition values of 10–70% in most layers and water contents commonly over 100% (weight to dry weight). The deposits constitute approximately 100,000 m^3. Soil samples from the current monitoring project show that the state of preservation is still good in most of the area, with a few exceptions (Dunlop 2007). The current policy for Bryggen is to not excavate but leave as much as possible for future generations. This requires the survival of all the evidence preserved in the cultural deposits through the maintenance of the physical, chemical and hydrogeological conditions that resulted in its preservation.

Hydrogeology

The hydrogeological situation of the site is characterised by Bryggen's position along the Vågen harbour, just beneath a mountain slope. The regional groundwater level is topographically induced, representing a subdued print of the topography with a regional groundwater flow towards Vågen. The regional phreatic level and hydraulic heads in deeper geological formations depend on the amount of precipitation, the infiltration capacity and the hydraulic characteristics of the underlying sediments, cultural deposits and bedrock.

Bryggen is located on a geological formation called the 'Bergen Arc', consisting of greenstones, phyllites and gneisses with a low primary hydraulic conductivity. During the construction of a railway tunnel to the northeast of Bryggen, high water bearing features such as zones of weakened bedrock, open faults and joints were mapped. Under the World Heritage Site, the bedrock surface occurs at about 12 m below sea level, rising gradually to about 2 m below sea level at the northeastern side of Bryggen. Old beach sands and underlying moraines cover the bedrock, representing the old coastline before the current quay was constructed. The wooden buildings were originally built on the beach along the coastline. After a fire, new buildings were constructed on top of the old foundations.

Although the regional groundwater flow is generally in a southwestern direction towards the harbour, local phreatic level, hydraulic head and chemistry are influenced by a complex interaction of multiple factors: (a) Precipitation and evaporation, influenced by buildings and terrain surface such as pavements and vegetation. Mean annual precipitation is 2250 mm, while mean annual evaporation is about 450 mm (source: Norwegian Meteorological Institute, Penman estimate). Terrain surface varies from cobbles, wood planking, asphalt to grassland. (b) Local variations in hydraulic properties such as natural alternation of sand, silt and clay, bedrock fractures, filling materials and trenches, causing heterogeneity or anisotropy of the hydraulic permeability. Water-bearing fractures have earlier been identified and mapped during tunnel construction in the direct vicinity of Bryggen. Archaeological investigations describe a large heterogeneity in filling materials and trenches, often constructed for dewatering the former tenements. (c) Tidal variations and salt-water intrusion, tidal variation being up to 2 m, while seawater intrusion and flooding with a mixture of seawater and rainwater causes a complex density-dependent flow system at the front of Bryggen (Golmen 2005). (d) Groundwater-regulating systems such as drainage, but also (unwanted) leakages in sewage and storm-water runoff pipes. According to the authorities, no known significant leakages in the domestic water-supply system exist. Diffuse leakages, damaged storm-water runoff pipes and wrong jointing of pipes are well known, but unquantifiable phenomena at Bryggen. (e) Underground infrastructure such as sheet piling and cellars. A sheet piling exists around the underground parking of the hotel on the former excavation site west of Bryggen, as well as around Bryggen's museum northwest of the hotel.

A simplified section is shown in Figure 3.

Methodology

Introduction

Holden et al. (2006) demonstrated from a research review on hydrological controls of waterlogged archaeological deposits, that both the quantity and quality of data on preservation status, as well as hydrological and chemical parameters collected during routine archaeological surveys, need to be improved. Any activity that changes either source pathways or the dominant water input may have an impact not just because of changes to the water table, but also because of changes to water chemistry. In order to understand the preservation potential fully, it is necessary to move away from studying the archaeological site as an isolated unit, since factors some distance away from the site of interest can be important for determining preservation (Holden et al. 2006). The methodology used at Bryggen follows this recommendation by using regional and local groundwater modelling parallel to field investigations, chemical analyses and monitoring.

Low phreatic levels and increased flux of oxygen in the subsurface, leading to decomposition of organic material and settling, currently threaten Bryggen. In order to better understand the water balance and factors influencing the phreatic levels at Bryggen, numerical modelling has been used parallel to field monitoring and laboratory analyses. The use of groundwater modelling in addition to 'traditional' monitoring efforts enables continuous adjustment and improvement of the monitoring strategy, thereby improving both the understanding of the hydrogeological system as well as giving feedback to the numerical model describing the system more adequately. Ultimately, the numerical model can then be used as a tool to predict changes in hydraulic head and phreatic levels as a consequence of natural or human changes forced upon it.

The field monitoring covers both the saturated and unsaturated zone and includes detailed chemical analysis of water and soil samples, continuous logging of piezometric levels, oxygen and soil moisture content, measurements of movement rates for buildings and soil surface, field measurements in test pits, as well as studies of archaeological material.

Numerical modelling

To improve the understanding of the hydrological system and the factors influencing the phreatic levels at Bryggen, a numerical groundwater model was constructed (de Beer et al. 2007). As with all hydrogeological model formulations, a model is a simplification of reality and inherently includes a number of errors. These errors are related to conceptualisation and descrip-

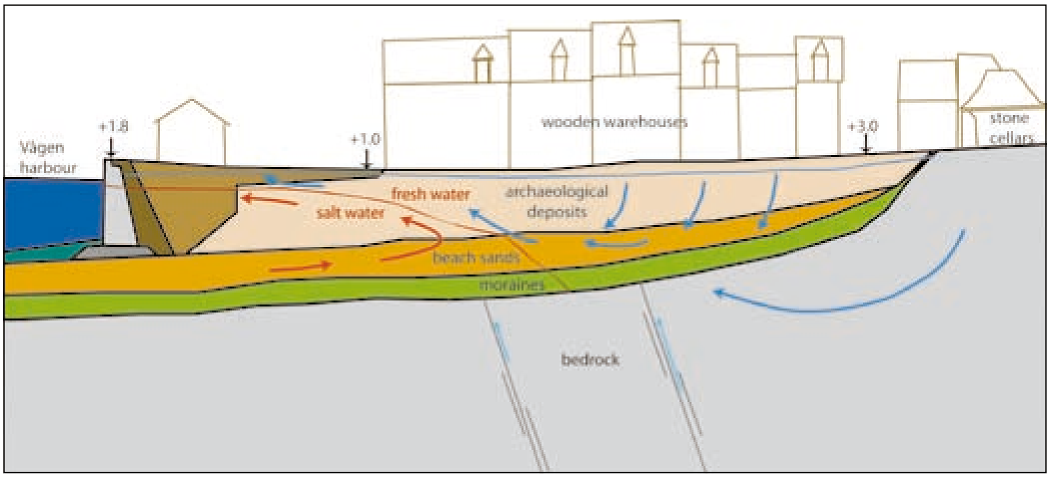

Figure 3. Model section from the rear of the old wooden settlement to the modern quay front (modified and extended after E. Mørk, Stiftelsen Bryggen).

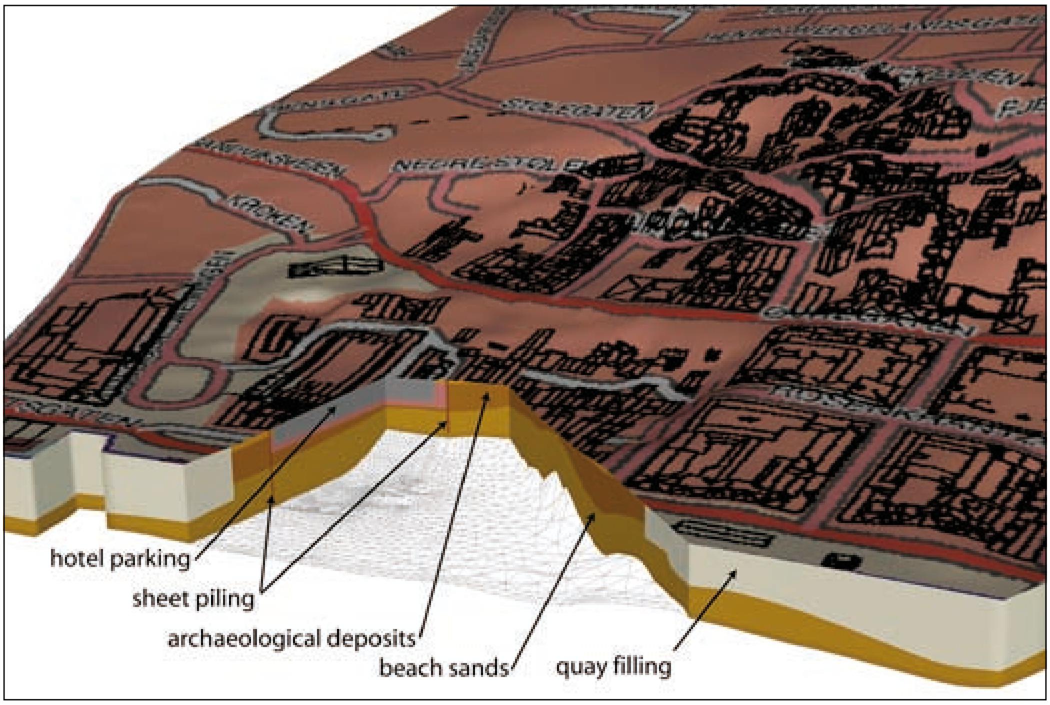

Figure 4. 3D block diagram of the topographical layers included in the groundwater model, showing schematisation of archaeological deposits, quay front and bedrock level.

tion of processes and interactions, estimates of parameter values, initial and boundary conditions, spatial and temporal variability and system stresses (Bierkens et al. 2006). In order to increase the usefulness of predictive simulations, it is necessary to reduce the uncertainties by indicating and quantifying the reliability of the results by verification against monitoring values. However, also early conceptual or intermediate (steady state) modelling stages provide valuable information and understanding of the hydrological system facilitating improvement of the monitoring program.

The finite element model code Feflow®5.3 (Diersch 2007) was used to simulate groundwater flow at Bryggen. Feflow® models flow, contaminant mass and heat-transport processes as coupled or separate phenomena. It is based on the physical conservation principles for mass, chemical species, linear momentum and energy in a transient and three-dimensional numerical analysis. For detailed description on the numerical calculations is referred to Diersch et al. (2007).

The model code has been chosen because of its ability to simulate fully three-dimensional transient groundwater flow, including density-driven flow (salt/fresh-water interaction and temperature effects), 3D anisotropy and flow within the unsaturated zone. Because the code is based on the finite element method, it provides an extremely flexible grid generation that is advantageous for use in urban areas with man-made structures such as sheet piling and drainage systems. In the unsaturated zone, insufficient soil-moisture measurements at various depths are currently available to adequately simulate unsaturated flow. The first slice in the model simulates a 'free' phreatic level and therefore changes its vertical position in time.

The chosen model area encloses the catchment area in which the study area is located. It extends from the Vågen harbour towards the topographically higher area of Fløyfjellet, behind Bryggen. Based on borehole descriptions, geological mapping, archaeological descriptions and construction drawings, a numerical model was constructed using 10 model layers with their estimated hydrogeological properties. The model layers were constructed using a digital terrain model, spatially interpreted borehole data and known construction depths for buildings.

A block diagram illustrating the schematised hydrogeological layering in the upper 5 layers of the numerical model is shown in Figure 4. The model consists of 158,200 6-noded triangular prisms, with a total of 88,572 nodes. The model mesh has been strongly refined along sheet piling and drainage systems. Boundary conditions have been applied along the harbour (tidal variations, salt water), top layer (daily precipitation) and known drainage systems (drainage level).

The hydraulic properties used prior to verification against monitoring values, are based on literature values, borehole descriptions and grain-size analyses. Parameter values were changed stepwise in a procedure of sensitivity analysis, steady-state calibration and subsequent transient calibration against registered piezometric levels, tidal variations and daily precipitation measurements (weather station 50540, Bergen-Florida).

For natural sediments, a range of applicable hydrogeological parameter values such as permeability, storativity and porosity exists, based on literature values, grain-size analyses or pumping tests. The hydraulic properties of an extremely heterogeneous archaeological deposit can only be deduced indirectly from groundwater-pressure measurements above, inside and below the deposit, in addition to a spatial distribution good enough to reflect effects of horizontal heterogeneity. However, a good description of the archaeological materials themselves, such as configuration and layering, together with a detailed description of the non-archaeological matrix between the archaeological artefacts, will give a qualitative indication of the hydrogeological behaviour to be expected. In the case of Bryggen, detailed knowledge about the configuration and layering of the archaeological structures has been gathered during archaeological excavations. One of the key features is horizontal layering of wooden elements together with known dewatering structures in and around the buried foundations. In model terms this is interpreted as a form of anisotropy, with a higher horizontal permeability than a vertical permeability and possible existence of preferential flow paths. Experiences with dewatering during excavation suggest relatively homogeneous, low permeability of the deposits. These qualitative data were used during calibration of the numerical model, in combination with monitored piezometric levels.

Field monitoring and laboratory analyses

In 2001–2005, a network of 14 observation wells (MB1 to MB14) was installed at selected locations within the archaeological deposits (Figure 5). One observation well (MB11) was installed in modern fill and archaeological and natural deposits about 150 m northeast (uphill) of Bryggen. Observation well MB11 was located further away from Bryggen in order to obtain undisturbed background data on the phreatic groundwater level, possibly reflecting the recharge pressure towards Bryggen. No other regional observation wells currently exist, which thus limits the interpretation of the regional groundwater flow system.

After a first (steady state) modelling study of the site, another 8 observation wells (MB16 to MB23) were installed in 2005–2006 (Figure 5). In order to place the site within its wider hydrological context, these observation wells were installed at specific locations within and outside the actual heritage site and at specific depths to determine vertical groundwater flow and chemistry changes. MB18 to MB22 are observation wells with a filter placed in the centre of the archaeological deposits, at depths of 6 to 7 m below the current terrain surface. MB23 and MB17 have their filter placed under the archaeological deposits, within the old sea bottom at a depth of approximately 11 to 12 m below the terrain surface (10 m below sea level). MB16 is located inside the hotel area, with a filter placed in remains of the archaeological deposits. MB15 is not yet installed.

When referring to 'sea level', the average sea level is referred to. At Bryggen, the average sea level is 1 cm above the national reference level NN1954.

All observation wells were measured manually with a monthly interval during the period 2001–2004. From December 15, 2006, 10 selected observation wells are equipped with data loggers (type Mini-Diver®, Van Essen) registering both piezometric level and temperature on an hourly basis. One data logger for registration of barometric pressure is installed in MB22 to compensate the other series for barometric variations. Sampling of groundwater in MB1–MB14 took place a couple of weeks after installation of each well, and for all wells simultaneously in June 2005. Further information on sampling method and detailed chemical analyses are given in Matthiesen (2008). On April 27, 2007, another 9 selected wells were sampled and analysed for major ions, pH, alkalinity and conductivity. In addition, pH and conductivity have been measured in the field for these 9 wells. An OTD-Diver® (Van

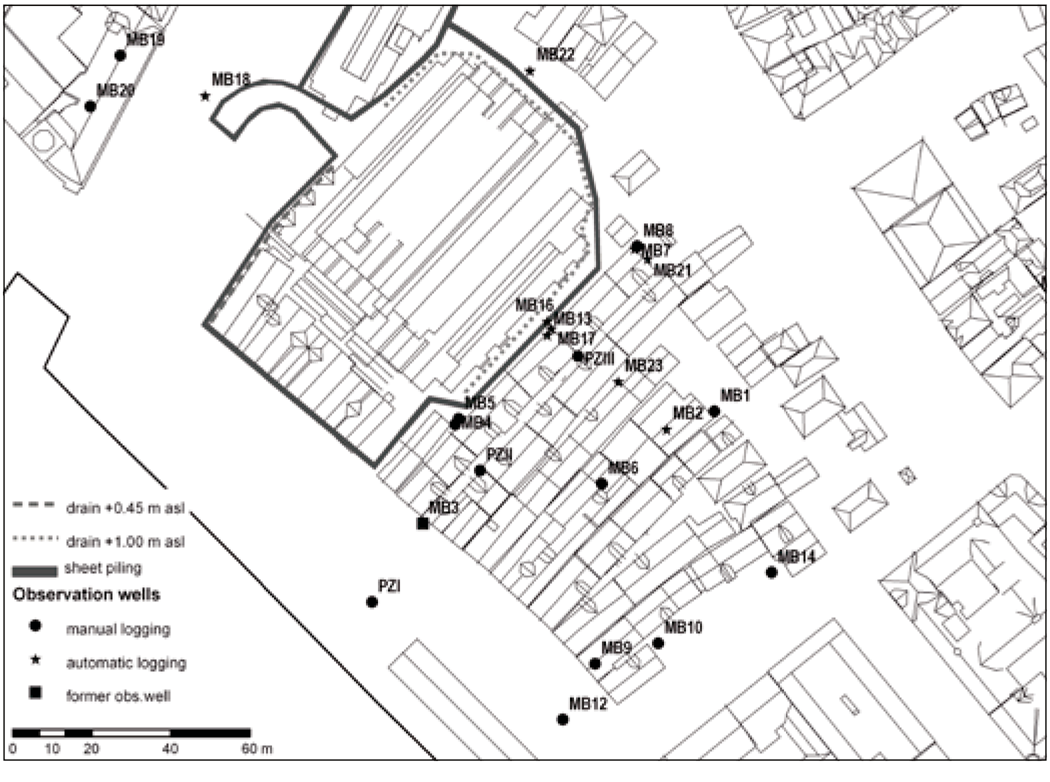

Figure 5. Situation overview with monitoring wells, drainage system and sheet piling.

Essen) was used for continuous logging of oxygen, temperature and piezometric level subsequently in MB1, 2, 3, 5, 6 and 7. A description of the method and detailed discussion of the results are given in Matthiesen (2008). At MB17, grain-size analyses have been performed on a depth-integrated soil sample from the old sea-bottom sand below the archaeological layers, at a depth of 10.6 to 11.4 m below the terrain surface. All analyses took place at accredited laboratories.

After a rough water-balance calculation performed with the numerical model, the drainage system under the current hotel was inspected on January 27, 2006. The discharge volume was measured and drainage water was sampled and analysed on major ions, pH, alkalinity, conductivity, turbidity and colour.

Results

Logger data and temporal variation

Groundwater monitoring results from observation wells MB13, MB22 and MB23 are shown in Figure 6 as representative examples for the groundwater behaviour at Bryggen. Relative variations in observation wells MB2 and MB18 were similar to MB13, MB7 gave the same response as MB22, while MB17 reflected a comparable result to MB23. Daily precipitation is shown for comparison. All piezometric levels have been corrected for atmospheric pressure variations.

The results from the groundwater loggers (Figure 6) show three distinct characteristics for both the local hydrological system at Bryggen as well as the influence of the wider hydrogeological situation:

1. At the rear side of Bryggen (upstream), a slow recession curve indicating a large aquifer system characterises the hydrological system. Observation wells MB7 and MB22 show groundwater variations on the order of 1 m during the measurement period, with an expected base flow level of around 0.5 m after a month with no precipitation.
2. Within the archaeological deposits, a strong correlation exists between the average observed tidal fluctuation in the Vågen harbour and the piezometric level. Piezometric levels are only indirectly influenced by precipitation due to the varying inflow from the recharge area and varying in- and outflow to and from the harbour. From March 21 to April 4, 2007, a rising groundwater trend in the observation wells within the archaeological deposits (MB2, MB13 and MB18) was observed, while there was no precipitation. Until April 9, there was no significant precipitation directly influencing the piezometric levels within the deposits. This groundwater rise coincided with a rise of the daily averaged tidal variations (see Figure 7).
3. Observation wells MB17 and MB23 show a rapid response with a delay of 2 hours with respect to the observed tidal fluctuation in the Vågen harbour. However, the amplitude of the groundwater variation is 90% damped in comparison with the observed tidal fluctuation, unless the observed sea level is higher than about 0.40 m above the average sea level (see Figures 8 and 9). At sea levels higher than 0.40 m, the piezometric levels are nearly equal to the tidal level. For comparison, the average high water level is 0.45 m above NN1954.

The measured hydraulic heads in the old beach sands under the archaeological deposits (MB17 and MB23) are permanently lower than the measured phreatic levels within the archaeological layers at Bryggen. Groundwater flow within the archaeological deposits is thus downward towards the underlying beach sands. The average head difference at MB2 is 70 cm, reduced to an average of 15 cm at MB13 (Bugården) due to a lowered phreatic level. The average horizontal groundwater flow direction is southwards to the Vågen harbour and partly westwards to the hotel area west of Bryggen. Figure 10 shows the general groundwater flow pattern for both phreatic groundwater and the underlying beach sands as simulated by the groundwater model.

Registered groundwater temperatures from December 15, 2006 to April 25, 2007 in all wells equipped with data loggers vary from 10°C to 14°C. MB11 and MB21 showed relatively low temperatures with respect to the average groundwater temperature. For comparison, the mean annual temperature in Bergen is 7.6°C.

Chemical analyses of groundwater

Matthiesen (2008) describes and discusses the results of chemical analyses of groundwater from 14 observation wells using an extended groundwater-analysis package covering 17 different chemical species. All 14 observation wells have filter positions within archaeological deposits. Correlations between chemical species show that even if the deposits are heterogeneous, the groundwater chemistry is not completely random across the site. A relatively simple model for the groundwater chemistry at Bryggen is presented and used to characterise areas with very good preservation conditions, and areas with more questionable conditions (Matthiesen 2008). A summary of the major ions is presented in Table 1 and graphically in Figure 11 along with new data from chemical analyses performed in 2007. These new data include chemical analyses of groundwater from observation wells below the archaeological deposits (MB17 and MB23) and from a location where archaeological deposits have been removed by excavation (MB22). Table 1 also includes results of chemical analyses of sampled water from the groundwater drainage system under the current hotel area.

Estimate of saturated hydraulic conductivity

During the installation of observation well MB17, a depth-integrated soil sample was taken from the sands below the archaeological deposits. A grain-size analysis was performed in order to obtain a better description of the material and an estimate of the saturated hydraulic conductivity. The grain-size distribution reflects a typical depositional environment of a beach zone, with a relative enrichment of both fine

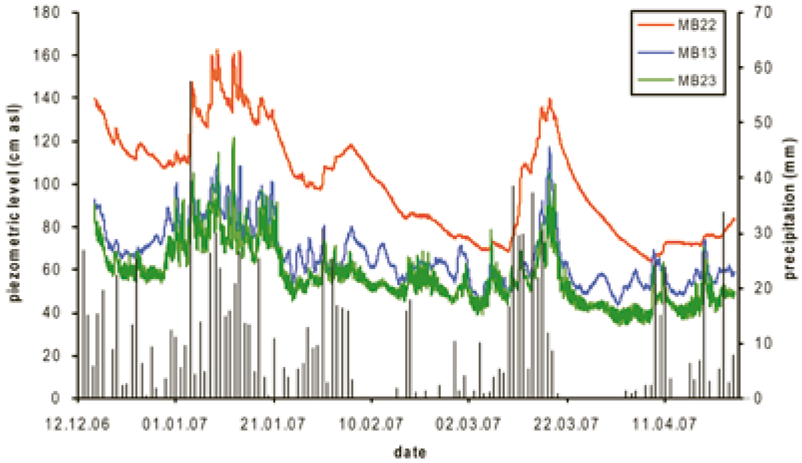

Figure 6. Representative hydraulic heads behind Bryggen (MB22), within archaeological deposits (MB13) and below archaeological deposits (MB23). Vertical lines represent precipitation.

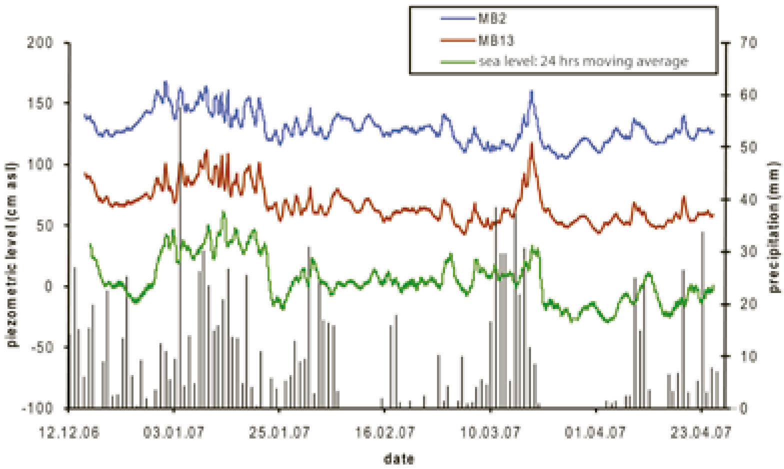

Figure 7. Comparison of 24 hours moving-average sea level with the piezometric level at MB2 and MB 13 (within archaeological deposits). Vertical lines represent precipitation.

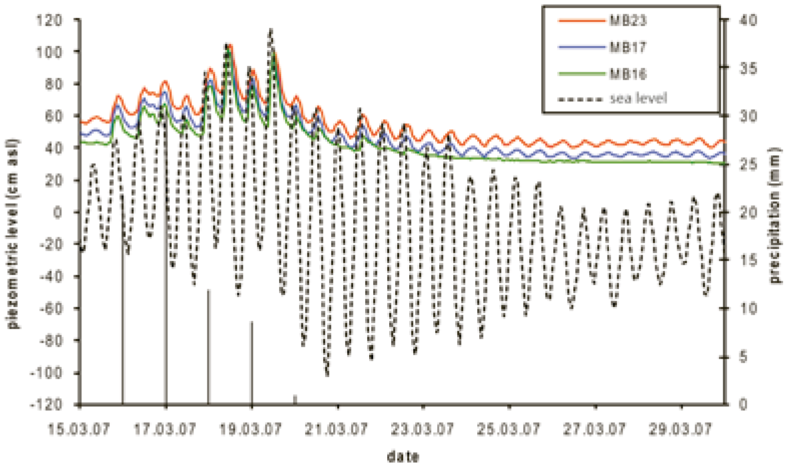

Figure 8. Tidal fluctuations below the archaeological deposits. Vertical lines represent precipitation.

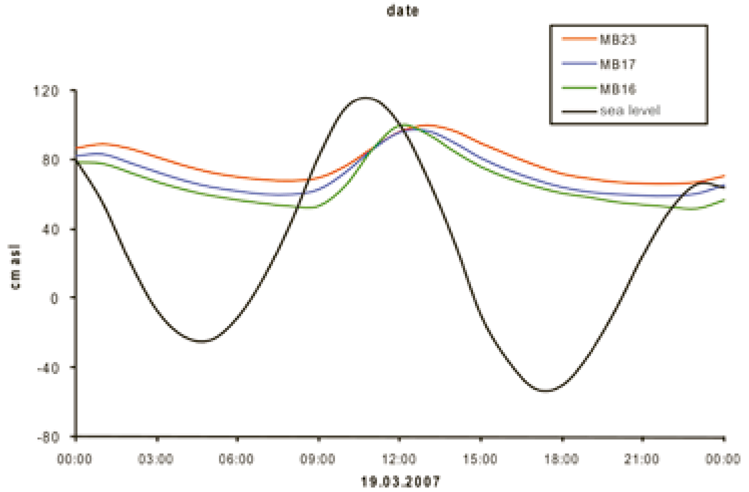

Figure 9. Time delay and damping of sea-level fluctuations to piezometric levels in MB16, MB17 and MB23.

Figure 10. Steady-state simulated phreatic level within the archaeological deposits and the hydraulic (pressure) head in the beach sediments below the archaeological deposits. Arrows indicate general horizontal flow direction.

*Table 1. Major ions from analyses of groundwater sampled on the 9th of June, 2005 (Matthiesen 2008). *Sampled on the 25th of April, 2007 (NGU). **Sampled on the 27th of January, 2006 (Multiconsult). All results are in mg l^{-1} except alkalinity, pH and electrical conductivity (EC). Sulphate is given as mg SO_4 l^{-1}. Molar weights of the different species are given in the second row, to allow easy calculation of the content to mmol l^{-1}.*

	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe^{2+}	Cl^-	SO_4^{2-}	Alkalinity	pH	EC
g mol^{-1}	*22.99*	*39.10*	*40.08*	*24.31*	*55.85*	*35.45*	*96.06*	*(meq l^{-1})*		*(mS m^{-1})*
MB1	140	9.7	21	6	24	120	2.6	4.9	7.1	85
MB2	410	26	130	24	1	470	4.5	13.1	6.9	250
MB2*	405	30	114	27	0.16	438	4.4	11.0	6.3	238
MB3	840	38	110	44	0.79	950	9.2	16.1	7.1	540
MB4	230	13	70	12	11	150	<0.5	7.4	7.0	160
MB5	4.6	1.8	9.3	<1	0.11	2.6	10	0.5	7.2	9
MB5*	7.1	1.38	7.9	1	0.01	8.3	3.4	0.5	6.9	10
MB6	790	42	110	43	1.6	1200	7	14.5	7.0	480
MB7	42	7.8	78	10	1.1	63	2.9	4.5	7.6	64
MB9	2700	86	150	250	1.8	4600	400	10.7	7.7	1400
MB10	760	39	200	30	3.1	2000	2	20.7	7.2	750
MB11	68	5.5	79	4	0.02	150	29	2.3	7.6	81
MB11*	14	1.8	23	1	0.012	13.4	5.5	0.8	7.0	16
MB12	410	40	300	60	1.2	710	16	23.4	7.0	420
MB13	110	13	88	14	3.3	130	2.3	11.9	7.2	150
MB13*	155	18	110	18	0.056	147	1.5	12.4	6.4	168
MB14	73	73	170	200	2.3	83	3.4	10.7	7.4	120
MB16*	382	26	206	52	0.274	627	20.5	12.9	6.4	188
MB17*	58	11	108	8	0.014	64.4	0.6	7.4	7.0	93
MB18*	43	13	191	22	19.3	62.3	1.9	10.5	6.4	120
MB22*	19	5.4	61	5	0.076	38.1	24.4	3.1	6.5	51
MB23*	164	22	242	20	0.046	126	2.8	14.3	6.6	66
drain**	202	15	80	22	0.008	318	38.2	4.0	7.2	146

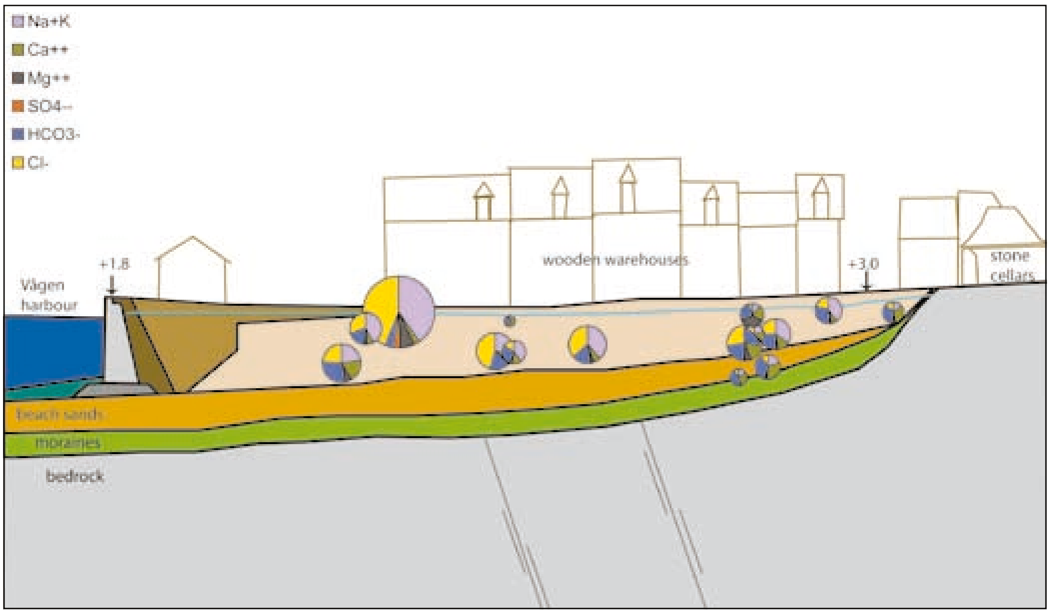

Figure 11. Graphical presentation of major ions in groundwater samples at monitoring wells, sampled in 2005 and 2007. See also Table 1. The left side of each circle represents the anions, while the right side represents the cations (in meq l^{-1}). HCO_3^- is estimated from the alkalinity. The area of the circle is proportional to the total amount of dissolved ions. MB11 is outside this picture, and MB8 is not represented as it was dry at the time of sampling.

(< 0.1 mm, d_{10} = 0.054 mm) and very coarse (> 5 mm, d_{60} = 2 mm) fractions due to washing out by wave activity. Based on a review of empirical formulae to estimate the saturated hydraulic conductivity (Odong 2007) from grain-size analyses, estimates on this highly bimodal, sorted sample are not applicable. We thus have to rely on in situ field testing, groundwater monitoring and model calibration.

Based on the depositional environment, a layering with coarser and finer fractions is expected, probably causing a significantly higher (semi-horizontal) hydraulic conductivity than empirically estimated by grain-size analysis of a depth-integrated sample. Pumping of observation well MB17 and MB23 during sampling indicates a significantly higher saturated hydraulic conductivity in the beach sediments below the archaeological layers than in the archaeological layers themselves. The rapid response of the piezometric pressure to tidal pressure variations (Figures 8 and 9) is a strong indication of a high-permeable deposit. Transient model calibration (ongoing) based on the measured piezometric monitoring indicates a saturated hydraulic conductivity of about 3.4 x 10^{-4} m s^{-1}, compared to 2 x 10^{-7} to 8 x 10^{-7} m s^{-1} for the archaeological deposits.

Groundwater model calibration

In Figure 10, representative model results are shown for the spatial groundwater variation. Transient model calibration is ongoing and is not discussed in this article. See de Beer (2005) for further details on boundary conditions and steady-state calibration.

Discussion

Groundwater: flow pattern and temporal variations

The hydrological regime within the archaeological deposits is a result of the interaction of tidal fluctuations in the Vågen harbour and the groundwater flow towards the deposits from the recharge area behind Bryggen. Due to the relatively low hydraulic permeability of the archaeological materials, groundwater changes are slow and dependent on the average fluctuations of the boundary conditions around, above and below the deposits.

Observation wells MB16, MB17 and MB23 (MB17 and MB23 below archaeological deposits) show a clear gradient towards the drainage system under the hotel, west of Bryggen. Rapid reactions indicate a good hydraulic connection. The head difference between MB16 (inside area enclosed by sheet piling) and MB13 (just outside sheet piling), both installed within archaeological deposits, is approximately 20 cm, indicating a limited hydraulic resistance over the sheet piling. The dynamic response of MB16, 17 and 18 confirms this by a slightly increased delay in response from MB16 towards MB23 (Figure 9), reflecting the input of tidal pressure from the hotel area towards Bryggen. The average head differences, the dynamic response and the grain-size analysis from MB17 support the impression of a good hydraulic connection between the drained hotel area and Bryggen, with flow via the old beach sands under the sheet piling. Construction drawings of the hotel show that the sheet piling probably does not reach the bedrock level at the front of the hotel. Groundwater flow through the beach sediments to the drainage system is thus unobstructed.

It is expected that the hydraulic head under the hotel is nearly horizontal due to a thick layer of high-permeable, coarse gravel under the parking lot. The drain installed at 1 m above sea level (asl) at the north and east side of the hotel only occasionally discharges groundwater, which supports this assumption. MB16 can thus be regarded as representative for the piezometric level below the entire hotel. It shows the lowest registered piezometric levels of all measured observation wells.

MB22 shows significantly higher piezometric levels than MB16, but in dry periods the registered levels steadily lower towards the levels of MB16. It shows that the current hydrological balance is not favourable for maintaining high phreatic levels in the archaeological deposits.

It is expected that both the observed horizontal flow towards the Vågen harbour as well as the downward flow within the archaeological deposits will be disturbed by high salt concentrations along the front of Bryggen. Seawater intrusion acts as a barrier for groundwater flow due to its higher density. Analyses of 61 soil samples from the archaeological deposits show that the chloride contents at the quay front are up to 3 orders of magnitude higher than at the back of Bryggen. The analyses also showed that the maximum chloride contents at the quay front were found a few metres down in the deposits, and that the contents decreased at greater depths (Matthiesen et al. 2007). In a natural situation, one would expect an upward flow against the salt-water wedge with a higher fluid density. However, this is dependent on the permeability of the underlying beach sands, its hydraulic connection with the harbour, occasional flooding, and the horizontal flow pressure from the recharge area through the beach sands and possible fractures in the bedrock. Further investigations at the front of Bryggen are required to resolve this issue.

Correlation with chemical data

In order to fully understand the impact of the hydrogeological situation on the preservation conditions, an attempt is made to relate the hydrological measurements with chemical analyses of the groundwater. The chemical composition of groundwater is the combined result of the composition of water that enters the hydrogeological system and reactions with minerals present in sediments and rocks, as well as degradation of organic material and other elements that may modify the water composition (Appelo et al. 2005). A description of the chemical composition of the groundwater within the archaeological deposits under Bryggen has been reported and discussed in Matthiesen (2008), and is further elaborated here.

At MB5, results from an automated oxygen logger show a dynamic environment characterised by abrupt piezometric level fluctuations up to 60 cm, with a sharp increase in oxygen content and a drop of temperature at the depth of the sensor at 1.4 m below sea level (Matthiesen 2008). During installation of MB5, a 30 cm-thick layer of sand and gravel was reported, surrounded by more dense organic-rich soil layers. The archaeological records document that at around this location and on this depth, a contemporary wharf-front was located, presumably indicated by a row of piles (Herteig 1990). According to the archaeological descriptions, a public thoroughfare was present between Bugården and Bredsgården, with a stake-lined drain beneath a stone paving. The drain or sewage was stabilised by a filling of gravel and wood chips of variable thickness providing the bedding for the untrimmed paving stones (Figure 12). Although no hard evidence exists, as there was no excavation

Figure 12. Stake-lined drain filled with gravel and wood chips beneath stone paving in the Bugården thoroughfare (Herteig 1990).

down to a depth of 1.4 m below sea level at MB5, at least the presence of a possible higher permeable element supports the dynamic hydrological environment. Also, a barrier effect of the sheet piling cannot be discarded, where groundwater is 'forced' along preferential flow paths by the sheet piling.

A negative correlation between the alkalinity and the filter depth is presented in Matthiesen (2008), along with positive correlations between alkalinity, ammonium and calcium as well as between potassium and ammonium. The addition of new results for observation wells MB17, MB23 and the drainage water show the increasing alkalinity with depth as reported by Matthiesen (2008), but a clear breach in this trend is observed within the old beach sands, where alkalinity drops significantly. In Figure 13, the alkalinity vs. filter depth is plotted.

The correlation between the alkalinity and filter depth may stem from a vertical or horizontal flow of groundwater. An increasing alkalinity with depth due to a groundwater formation process where groundwater slowly percolates down through the soil layers, gradually picking up bicarbonate and other ions from decaying organic material or from dissolution of carbonates, is supported by the measurements of the piezometric

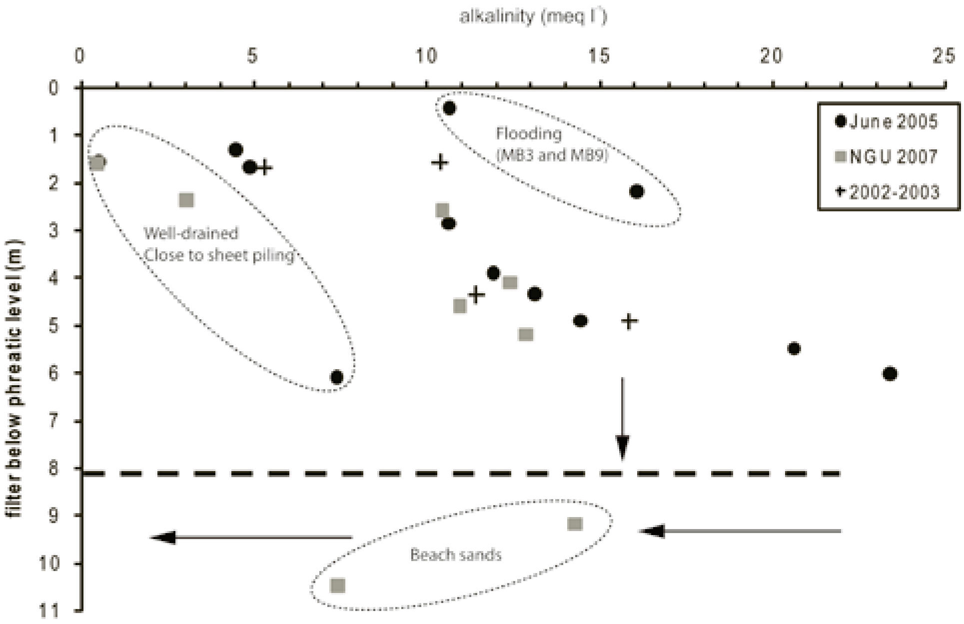

Figure 13. Alkalinity vs. filter depth below the phreatic level at each observation well at the time of sampling. Exceptions from the trend are indicated and general flow direction is shown with arrows.

heads at different depths. A downward groundwater flow exists. However, the alkalinity drops dramatically at depths under the archaeological deposits, indicating an abrupt change of the hydrological environment. Water with high alkalinity from the archaeological deposits is mixed with possibly younger, more diluted groundwater in the permeable beach sediments. Although carbonate is present in the beach sediments (shells), the groundwater does not reflect this by a further rise in alkalinity, possibly due to the highly dynamic environment with relatively short retention times. A similar plot of groundwater conductivity vs. depth gives the same results.

Matthiesen (2008) discerns three types of groundwater: (1) Seawater-influenced groundwater with a high content of Na^+, Cl^-, Mg^{2+}, SO_4^{2-} and K^+. (2) Slowly downward percolating groundwater, with high contents of reduced species as well as increasing HCO_3^-, NH_4^+, Ca^{2+} and K^+ with depth. (3) Rainwater with some oxygen and nitrate, but overall a low concentration of ions. An additional, fourth type of groundwater, may be distinguished based on chemical analyses in MB17, MB23 and flow measurements: (4) Groundwater between the archaeological layers and the bedrock, influenced by upward flow from the bedrock and downward flow from the archaeological deposits. This mixed water type has a lower total amount of dissolved ions compared to 'type 1' and 'type 2', but relatively high HCO_3^-, Na^+, Ca^{2+} and K^+ concentrations, possibly due to a more dynamic environment and short retention times.

Numerical model

Figure 10 shows the average simulated phreatic level within the archaeological deposits (blue contours) as well as the average hydraulic head in the underlying beach sediments at approximately 11 m below the terrain surface (red contours). Flowlines have been added to illustrate the general horizontal groundwater flow pattern. Comparison of the contours in both soil layers shows downward flow under Bryggen. Under the southwestern part of the hotel area, an upward flow towards the drain system at 0.45 m asl is visible. However, due to the very high permeability and a hydraulic connection between the drainage system and the harbour, the vertical flow direction under the hotel area changes with the tide. When the tide is higher than 0.40 m asl, temporary infiltration from the drainage system occurs.

At the eastern part of Bryggen, calculated piezometric levels between the beach sediments and the archaeological deposits are almost equal, indicating a limited vertical flow. This is probably caused by a relatively high bedrock level in this area, acting as a barrier for vertical groundwater flow. From historical maps, the beach sediments are thin or even absent in the eastern area of Bryggen. A rock outcrop is present at the far northeastern side of the study area and no significant settling of the ground or buildings is currently measured, which supports this hypothesis.

The groundwater model simulates upward flow under the quay area due to salt-water intrusion. Fresh water from the archaeological deposits and the underlying beach sediments is pushed upwards against a salt-water wedge extending to the front buildings of Bryggen. Seawater intrusion thus forms a hydrological barrier for groundwater flow, which changes the water balance under Bryggen. A comparative model simulation with a fresh-water boundary condition instead of a salt-water boundary condition results in a significant decrease (around 50%) of the discharge volume from the drainage system under the hotel area. It must be stressed that these calculations are based on the assumed boundary condition that the Vågen harbour forms a hydrological barrier with salt water down to about 2 m below the harbour bottom. Depending on the permeability of the old beach sands, depth and permeability of the harbour bedding and the inland hydraulic head, freshwater outflow towards the Vågen harbour might occur via the beach sediments and bedrock. An indication of this possible flow direction comes from soil and groundwater analyses at MB12 (Matthiesen 2006a, b), showing lower chloride concentrations at greater depths. A multilevel monitoring well, including the old beach sediments at the front of Bryggen, was installed in the autumn of 2007. This well should provide further evidence of the validity of the applied boundary condition.

The marked area in Figure 10 indicates bad preservation conditions due to a lowered phreatic level. This is observed and carefully registered in archaeological investigation samples taken during drilling of the observation wells (Christensson et al. 2007).

Conclusions and future work

Conclusions

Two hypotheses (H1 and H2) were tested:

H1. A combined hydrological and archaeological approach leads to a more fundamental understanding and thus improved protection of the archaeological site in situ. The use of 'traditional' groundwater monitoring and chemical analyses in combination with numerical groundwater modelling is a useful routine in increasing the understanding of the hydrological system of a complex archaeological site, such as Bryggen. The following conclusions could be drawn due to the combination of a hydrological, geochemical and archaeological approach:

- The phreatic level is the most important factor for preservation of organic material. Intensifying the monitoring frequency within the archaeological deposits to an hourly interval showed that the phreatic level strongly correlates to the average observed tidal fluctuation in the Vågen harbour. Precipitation has a minor, indirect effect on the phreatic level. Before the high frequency monitoring started in 2006, it was concluded that the phreatic level is steady and variations were related to precipitation, based on a monitoring interval of 2 months.
- Placing observation wells, monitoring hydraulic head and analysing groundwater at different locations outside and below the archaeological deposits themselves provided new information on possible threats to the archaeological layers to be preserved. A good hydraulic connection and relatively high saturated conductivities between the (earlier ignored) beach sediments below the archaeological deposits seem to have a major impact on the long-term phreatic levels. Although reaction time may be in terms of decades due to the very low saturated conductivity of the organic archaeological layers, a change in the water balance by extracting water from the underlying beach sediments (at a location not necessarily below Bryggen) will eventually cause a lowering of the phreatic level over a larger area if not compensated by additional inflow elsewhere.
- Numerical groundwater modelling provided a better understanding of the hydrological processes involved by forcing us to look beyond the archaeological site to be preserved. It resulted in preliminary quantitative measures of the water balance at Bryggen. The groundwater model helped us to identify sensitive parameters that control the phreatic level and thus the preservation conditions. This knowledge is used to design measures for re-establishing the phreatic level at Bryggen and creating a stable water-balance condition. The groundwater model will be an important tool to design and evaluate technical measures involved to create a system in balance where further deterioration and settling is minimised.

Generally, from an archaeological perspective, the above-described approach results in identification of important factors influencing preservation conditions, specifically the phreatic level and the processes leading to the chemical composition of groundwater surrounding archaeological deposits. In situ preservation requires a thorough understanding of the regional and local hydrogeological system in order to assess possible protective measures and prevent actions leading to deterioration of archaeological material. An interdisciplinary approach combining hydrogeology, chemistry and archaeology is, therefore, necessary to obtain a full understanding of preservation conditions.

H2. A combined hydrological and archaeological approach improves identification of archaeological deposits at risk. The use of groundwater modelling in addition to 'traditional' monitoring efforts enables continuous adjustment and improvement of the monitoring strategy, which in turn improves the understanding of the hydrogeological system and gives feedback to the numerical model describing the system more adequately. The improved hydrogeological understanding of the site within its wider environment leads to identification of areas with unfavourable conditions for archaeological preservation, thus improving identification of archaeological deposits at risk.

Future work

Once transient calibration of the numerical groundwater model of Bryggen and surroundings is satisfactory, the model will also help to predict impacts of landscape and climate change. The urban landscape around Bryggen changes continuously with new buildings and infrastructure, renewal of drainage and sewage systems, changes of pavements and so on. Urban development has taken place since Bryggen was built and certainly has had its impact on the hydrological situation. The groundwater model facilitates us in simulating effects of those urban changes. Consequences of climate change, which may lead to increased precipitation and a sea-level rise, can be estimated with the groundwater model, resulting in valuable management information for in situ preservation of the archaeological deposits.

The current intensive monitoring program will be reduced to an effective, permanent monitoring scheme. Once detailed data analysis and hydrological modelling have clarified the underlying processes, the number of wells and the frequency of monitoring can be adjusted to a minimum level necessary to provide essential information for preservation management. At complex sites, the use of groundwater modelling in addition to monitoring is a cost-effective alternative to simply gathering more monitoring data and waiting for a significant number of data to show a trend.

A future challenge will be a more quantitative approach by extending the numerical groundwater model with geochemical data. The hydrogeochemical model may then be used to quantify chemical changes in the groundwater that control preservation conditions. The unsaturated zone is of major importance for preservation conditions. An extension of the groundwater model to also include the unsaturated zone may, therefore, be a valuable improvement.

Since November 8, 2006, continuous logging of soil moisture content is carried out with 4 soil-moisture sensors at depths of 2.00, 2.45, 2.83 and 3.29 m asl, at a former small archaeological excavation between observation wells MB7 and MB21. A challenge will be to use these field data and obtain other suitable field data for calibrating soil water content and unsaturated flow.

The registered relatively high groundwater temperatures caused by urbanisation need to be further elaborated with regard to possible effects on preservation conditions. Understanding the above-mentioned processes will then allow for more generic risk-mapping tools to be developed

.

Acknowledgements

The monitoring at Bryggen is funded by the Directorate of Cultural Heritage in Norway. The support of all participants in the Bryggen Project is very much appreciated. We would like to thank Sylvi Gaut and Bjørn Frengstad for carefully reading the manuscript. The helpful comments of Mike Corfield and one anonymous reviewer are highly appreciated.

References

Appelo, C.A.J. and Postma, D. (2005) *Geochemistry, groundwater and pollution*. 2nd edition, Balkema, Leiden, 649 pp.

Beer, H. de (2005) Hydrogeologisk modellering Bryggen, Bergen: midlertidig rapport. *NGU Rapport 2005.080*, 44 pp.

Beer, H., de, Christensson A., Jensen J.A. and Matthiesen, H. (2007) A numerical model to support archaeological preservation strategies. *Journal of Bio- and Archaeological Studies*. Proceedings from Preservation of Archaeological Remains in situ 3, Amsterdam, in press.

Bierkens, M.F.P., Gehrels, J.C.and Kovar, K. (eds.) (2006) International Commission on Groundwater and TNO Built Environment and Geosciences 2006: *Calibration and reliability in groundwater modelling: from uncertainty to decision making*. IAHS Publication **304**, Wallingford, 316 pp.

Christensson, A., Paszkowski, Z., Spriggs, J.A. and Verhoef, L. (2004) *Safeguarding historic waterfront sites. Bryggen in Bergen as a case study*. 1st edition. Stiftelsen Bryggen and Polytechnika Szczecinska, Bergen, Norway, 338 pp.

Christensson, A., Dunlop, R., Beer, H. de, Jensen, J.A. and Matthiesen, H. (2007) The project "Safeguarding Historic Waterfronts - Bryggen in Bergen". *Journal of Bio- and Archaeological Studies*. Proceedings of Preserving Archaeological Remains in situ 3, Amsterdam, in press.

Corfield, M., Hinton, P., Nixon, T. and Pollard, M. (1998) Preserving archaeological remains in situ. Proceedings of the conference 1st–3rd April, 1996. Museum of London Archaeology service, English Heritage, London.

Diersch H.-J.G. (2007) FEFLOW Finite Element Subsurface Flow and Transport Simulation System, Reference Manual, version 5.3.

Dunlop, R. (2007) Archaeological recording in connection with monitoring in Norway's medieval towns. *Journal of Bio- and Archaeological Studies*. Proceedings of Preserving Archaeological Remains in situ 3, Amsterdam, in press.

Golmen, L.G. (2005) Bryggen in Bergen. Vassinntrengning i fundament og bolverk. Resultat av målingar vinteren/våren 2005. *Norwegian Institute for Water Research, Report 5047–2005*, 34 pp.

Herteig, A.E. (1969) *Kongers havn og handels sete. Fra de arkeologiske undersøkelser på Bryggen i Bergen 1955–68*. Aschehoug, Oslo, 224 pp.

Herteig, A.E. (1985) *The archaeological excavations at Bryggen, "the German wharf", in Bergen, 1955–68: excavation, stratigraphy, chronology, field-documentation*. The Bryggen Papers Main Series, Volume 1, Universitetsforlaget, 46 pp.

Herteig, A.E. (1990) *The buildings at Bryggen: their topographical and chronological development*. Universitetsforlaget, Oslo, 151 pp.

Holden, J., West, L.J., Howard, A.J., Maxfield, E., Panter, I. and Oxley, J. (2006) Hydrological controls of in situ preservation of waterlogged archaeological deposits. *Earth-Science Reviews*, **78**, 59–83.

Jensen, J.A. and Stordal, A.D. (2004) Miljøovervåkningsprosjekt Bugården-Bryggen i Bergen, FoU-prosjekt. Grunnundersøkelser og setningsmålinger. *Multiconsult, avdeling Noteby Report 400962*, 15 pp.

Matthiesen, H. (2006a) Composition of soil and groundwater at dipwells MB12, 10, 14 and 13 Bryggen, Bergen. National Museum of Denmark, Department of Conservation, Lyngby, *Report 12027-0004*, 37 pp. Available online from www.natmus.dk/sw8893.asp

Matthiesen, H. (2006b) Groundwater composition at Bryggen in Bergen June 2005 – an evaluation of the use of water samples for monitoring preservation conditions. National Museum of Denmark, Department of Conservation, Lyngby, *Report 12027-0005*, 28 pp. Available online from www.natmus.dk/sw8893.asp

Matthiesen, H. (2008) Detailed chemical analyses of groundwater as a tool for monitoring urban archaeological deposits: results from Bryggen in Bergen. *Journal of Archaeological Science*, **35**, 1378–1388.

Matthiesen, H., Dunlop, R., Jensen, J.A., Beer, H. de, and Christensson, A. (2007) Monitoring of preservation conditions and evaluation of decay rates of urban deposits – results form the first five years of monitoring at Bryggen in Bergen. *Journal of Bio- and Archaeological Studies*. Proceedings of Preserving Archaeological Remains in Situ 3, Amsterdam, in press.

Myrvoll, S., Golembnic, A. and Dunlop, A.R. (1983) The Finnegården project. Paper stencil, Riksantikvarens utgravningskontor, 1983.

Nixon, T. (2004) Preserving archaeological remains in situ? Proceedings of the 2nd conference 12–14 September, 2001. Museum of London Archaeology service, pp. 254–260.

Odong, J. (2007) Evaluation of empirical formulae for determination of hydraulic conductivity based on grains-size analysis. *Journal of American Science*, **3**, 54–60.

Valetta Treaty (1992) European Convention on the Protection of the Archaeological Heritage (Revised). ETS no. 143.

Unesco (2008) *Operational Guidelines for the Implementation of the World Heritage Convention*. Intergovernmental committee for the protection of the world cultural and natural heritage, World Heritage Centre. WHC 08/01, January 2008, 173 pp.