Transient, variable density groundwater flow modelling as a tool for developing a preservation strategy for waterlogged archaeological deposits at Bryggen in Bergen, Norway

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ABSTRACT: Deterioration of archaeological material often occurs as a consequence of change in the water balance. To better understand the preservation conditions and to protect archaeological deposits, it is necessary for any archaeological site to be placed within its wider natural environment, to understand the natural hydrological balance and possible changes that are being forced upon it by nature or humans. The preservation conditions within the cultural deposits at World Heritage Site Bryggen in Bergen, Norway, have a significant correlation with groundwater flow dynamics. It is demonstrated that transient, variable density groundwater modelling together with other hydrological investigation methods, results in an effective routine to better understand the preservation conditions in complex surroundings and therefore to improve protection of the deposits.

INTRODUCTION

In situ preservation is often preferred to excavation as a sensible way to manage non-renewable archaeological resources. 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. 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. Preservation conditions of archaeological remains preserved in situ are dependent on both the natural environment and changes to this environment (Holden et al., 2006). Most variables influencing the preservation conditions are 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 hydrological balance and possible changes that are being forced upon it by nature or human activities. The monitoring and modelling work that is ongoing at the World Heritage Site of Bryggen show the benefits of this multidisciplinary approach.

SITE DESCRIPTION

History and archaeology

Bryggen in Bergen 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).

Figure 1: Traditional timber buildings of Bryggen, interconnected in long rows with narrow straits in-between. Right: photo from the archaeological excavations during 1955-68.
In 1955, a large fire destroyed about a third of Bryggen's buildings, on the western part of the site. Extensive archaeological excavations took place in the period from 1955 to 1968 by A.E. Herteig. It uncovered up to 8 m thick organic cultural deposits covering the entire span of Bryggen's history. The excavations also revealed an excellent state of preservation and a huge amount of information in the deposits (Herteig 1985). In 1979, a hotel was constructed at the former excavation area. The construction included a parking lot down to about 3 m below average sea level enclosed by sheet piling and underlain by a drainage system.

In 1979, Bryggen was included in the World Heritage list. The total system comprising the World Heritage site of 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. 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 2](image.png)

**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).

The archaeological deposits at Bryggen 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 m³, with varying preservation conditions, from excellent to intermediate zones with less ideal preservation conditions as well as zones with very poor preservation conditions (Matthiesen 2008). The current archaeological 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 characterized 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, infiltration capacities and hydraulic characteristics of the underlying sediments, cultural deposits and bedrock. A conceptual model section is shown in figure 3.

Figure 3: Conceptual model section.

Bryggen is located on a geological formation called the ‘Bergen Arc’, consisting of low permeable greenstones, phyllites and gneisses, but with identified better permeable features such as zones of weakened bedrock, open faults and joints. Under the World Heritage Site itself, the bedrock surface occurs at about 12 m below sea level, rising gradually towards the northeastern side of Bryggen. Old beach sands and underlying moraines cover the bedrock, representing the old coastline before the current quay was constructed (figure 2). 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. A simplified model section of the local situation below Bryggen is shown in figure 4.

Figure 4: Conceptual model section from the rear of the wooden settlement to the modern quay front (modified and extended after E. Mørk, Stiftelsen Bryggen).

Although the regional groundwater flow is generally in a southwestern direction towards the harbour, local groundwater heads and chemistry are influenced by a complex interaction of multiple factors:
(a) Precipitation and evaporation. Mean yearly precipitation is 2250 mm, evaporation about 450 mm.
(b) Local variations in hydraulic properties such as natural alternation of sand, silt and clay, bedrock fractures, filling materials and trenches, causing heterogeneity and anisotropy of the hydraulic permeability. Archaeological investigations describe heterogeneity in filling materials and trenches, often constructed for dewatering the former tenements.
(c) Tidal variations and salt-water intrusion. Tidal variation up to 2 m. Seawater intrusion and flooding with a mixture of sea- and rainwater cause a complex density dependent flow system at the front of Bryggen.
(d) Groundwater-regulating systems such as drainage, but also (unwanted) leakages in sewage and storm-water runoff pipes. 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.
INVESTIGATION RESULTS

Methodology

Low phreatic levels and increased flux of oxygen in the subsurface, leading to decomposition of organic material and settling, currently threaten Bryggen. Current settlement rates are up to 8 mm per year and increasing due to disappearing organic archaeological material beneath our feet.

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, needed improvement. 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. The methodology used at Bryggen follows this recommendation by using regional and local groundwater modelling parallel to field investigations, chemical analyses and monitoring.

The use of groundwater modelling in addition to ‘traditional’ field 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 (figure 5).

Figure 5: Diagram showing interdisciplinary system characterization.

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 using Feflow® 5.3. 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. It provides a flexible grid generation that is advantageous for use in urban areas with man-made structures such as sheet piling and drainage systems. 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 behind Bryggen.

As with all deterministic hydrogeological model formulations, the model is a simplification of reality and inherently includes a number of errors, related to conceptualization, parameter estimations, process description, boundary conditions, spatial variability and so on. 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, it must be
stressed here that also early conceptual or intermediate (steady state) modelling stages provide valuable information and understanding of the hydrological system, thereby facilitating improvement of the monitoring program.

A numerical model was constructed using 10 model layers with their estimated hydrogeological properties. The model layers were constructed using a digital terrain model, borehole data and known construction depths for buildings. A block diagram illustrating the schematized hydrogeological layering in the upper 5 layers of the numerical model is shown in figure 6.

![Figure 6: 3D block diagram of the upper topographical layers included in the groundwater model, showing schematization of archaeological deposits, quay front and bedrock level.](image)

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. 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 artifacts, will give a qualitative indication of the hydrogeological behavior 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 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 archaeological excavation suggest relatively homogeneous, low permeability of the deposits. These mostly qualitative data were used during calibration of the numerical model, in combination with measured piezometric levels.
Observations

Hydraulic head
In 2001−2005, a network of 14 observation wells was installed at selected locations within the archaeological deposits. One observation well was installed in modern fill and archaeological and natural deposits about 150 m northeast (uphill) of Bryggen. After a first (steady state) modelling study of the site, another 11 observation wells were installed in the period from 2005 to 2008. A situation overview for 2007 is shown in figure 7.

Figure 7: Situation overview with observation wells, drainage system and sheet piling (situation 2007).

The 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. Besides regular manual measurements of groundwater head, a selection of 12 observation wells is equipped with automatic sensors since 2006, measuring groundwater pressure and temperature once every hour.

The results from the automatic sensors show 3 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), slow recession curves indicating a large aquifer system characterize the hydrological system.
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.
3. Below the archaeological deposits, in the old beach sediments, observation wells show a rapid response with a delay of only 2 hours with respect to the observed tidal fluctuation in the Vågen harbour. However, the amplitude of the groundwater variation is 90% damped with respect to the tidal fluctuation, unless the observed sea level is higher than about 0.40 m above average sea level. At sea levels higher than 0.40 m, the piezometric levels are nearly equal to the tidal level. The measured hydraulic heads in the old beach sediments are permanently lower than the measured phreatic levels within the archaeological layers at Bryggen, indicating downward groundwater flow within the archaeological deposits. The average horizontal groundwater flow
direction is to the Vågen harbour and partly westward to the hotel area west of Bryggen with a drainage system (figure 8).

The groundwater level within the archaeological deposits is lowered due to leakage of the sheet piling around the hotel parking lot and subsequent flow towards the drainage system. The primary flow path appears to be higher permeable beach sediments below the archaeological deposits, thereby increasing the influenced area below the site.

Figure 8: Steady state simulated phreatic level within the archaeological deposits and the hydraulic (pressure) head in the beach sediments below. Arrows indicate horizontal flow.

Temperature
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. The mean annual temperature in Bergen is 7.6°C. It is concluded that the urban underground is significantly heated up by buildings above and under the ground surface.

Chemical analyses
Sampling of groundwater took place a couple of weeks after installation of each well, and for all available wells simultaneously in 2005 and 2008. Information on sampling, detailed groundwater chemistry and its relation to preservation conditions is given by Matthiesen (2008). In this paper only chloride is discussed as it influences flow conditions due to density differences.

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 meters down in the deposits, and that the contents decreased at greater depths. 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. Recent measurements in two wells at different depths along the front of Bryggen show an upward groundwater flow. The exact flow system is still part of investigation.
The numerical model was used to calculate a water balance and estimate the amount of water that is removed from the system through the drainage system below the hotel parking lot, as a leakage from the system. This amount has also been measured once. Including density driven flow along the Vågen harbour resulted in an increase of the calculated "leakage" of about 50%.

CONCLUSIONS

The use of 'traditional' groundwater monitoring and chemical analyses in combination with numerical groundwater modelling has been proved to be a useful routine to increase the understanding of the hydrological system of a complex archaeological site, such as Bryggen. For Bryggen, the main conclusions are:

- The phreatic level is the most important factor for preservation of organic material and is strongly related to tidal pressure variations. Precipitation has a minor, indirect effect on the phreatic level. Until high frequency monitoring started in 2006, it was incorrectly concluded that the phreatic level is steady and variations were related to precipitation, based on a monitoring interval of 2 months.
- Observation wells, registration of hydraulic head and groundwater analyses at different locations outside and below the archaeological deposits themselves provided new information on possible threats to the archaeological layers. 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 permeability of the organic archaeological layers.
- Transient variable density flow 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 to identify sensitive parameters that control the phreatic level and thus the preservation conditions. This knowledge is now 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 minimized.

In general, 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. An interdisciplinary approach combining hydrogeology, chemistry and archaeology is, at least at complex sites, necessary to obtain a full understanding of preservation conditions. Groundwater modelling as an integral part in a combined hydrological and archaeological approach improves identification and protection of waterlogged archaeological deposits at risk.

REFERENCES


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