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Groundwater composition
at Bryggen in Bergen:
Temporal and spatial va-
riation, May 2008



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Title:
Ground water composition at Bryggen in Bergen: Temporal and spatial variation, May 2008

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Summary:

On request from Riksantikvaren in Norway, the composition of 28 groundwater samples from dipwells at Bryggen in Bergen are presented and commented on. The main focus is on the spatial and temporal variation in the composition, and the implications for the preservation conditions for the cultural layers below Bryggen.

The data confirms and refines the conceptual model for groundwater chemistry and –formation earlier established for the Bryggen area (de Beer & Matthiesen, 2008). It is confirmed that there is a distinct correlation between the depth and the composition of the water in the cultural layers, and this has now also been shown for methane. Thus, the deeper the water intake, the more stagnant conditions and the less dilution with rainwater is observed. Samples from the natural deposits beneath the cultural layers indicate that groundwater flows from the archaeological deposits and downwards, which means that the archaeological deposits themselves are hardly influenced by the water composition found underneath. Near the quay front there is an input of seawater to some of the cultural layers, which may give a substantial decay of organic material by sulphate reduction (Matthiesen, 2008a). Dipwells MB19 and MB20 under Slottsgaten 1 (north-west of the hotel) have been sampled for the first time, showing a high temperature and a high iron content compared to other dipwells on Bryggen.

The ground water data from May 2008 are compared to results from earlier sampling campaigns in 2002-2007. Generally there is only modest temporal variation in the water composition. The exceptions are dipwells MB5, MB9 and MB11 showing very dynamic conditions, which is in correspondence with earlier observations. MB6 shows some variation, which is surprising and should be confirmed.

The data may be further evaluated in a combined hydrological-geochemical model. Future monitoring should be based on automated loggers as far as possible. Future sampling should focus on the harbour front area, near the sheet pile and possibly under Slottsgaten 1, analysing only a few

chemical species in the samples. Next full sampling in all dipwells and analysis for all chemical species should take place in 3-5 years time.

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Appendix 1: Results from chemical analysis of groundwater from May 2008, and observations made during sampling

Introduction

At Bryggen in Bergen the buildings and their foundations are presently being restored. In this context the state of preservation and possible threats against the cultural layers underneath the buildings are discussed. The measurement of high settling rates of the soil surface at several places in the area has made this discussion even more relevant (Jensen, 2007).

A total of 31 dipwells have been installed around the Bryggen area since 2001 to allow the measurement of groundwater level/pressure and to take water samples for the evaluation of preservation conditions. In 2002 water samples were taken from the first two dipwells, and in June 2005 simultaneous sampling was made in the 14 dipwells installed at that time. The results were discussed in terms of how they represent the preservation conditions (Matthiesen, 2006) and presented in a scientific paper (Matthiesen, 2008b). In April 2007 a partial sampling covering 9 dipwells was made, and the results were included in de Beer & Matthiesen (2008). Most recently, in May 2008, a simultaneous sampling was made in the 31 dipwells that are present today, resulting in 28 water samples. The National Museum of Denmark has been contracted by Riksantikvaren to interpret the results and to evaluate if they indicate a change in the preservation conditions in the cultural layers below Bryggen.

Site and methods

An overview of the dipwells installed from 2001 to 2007 is presented in Figure 1.

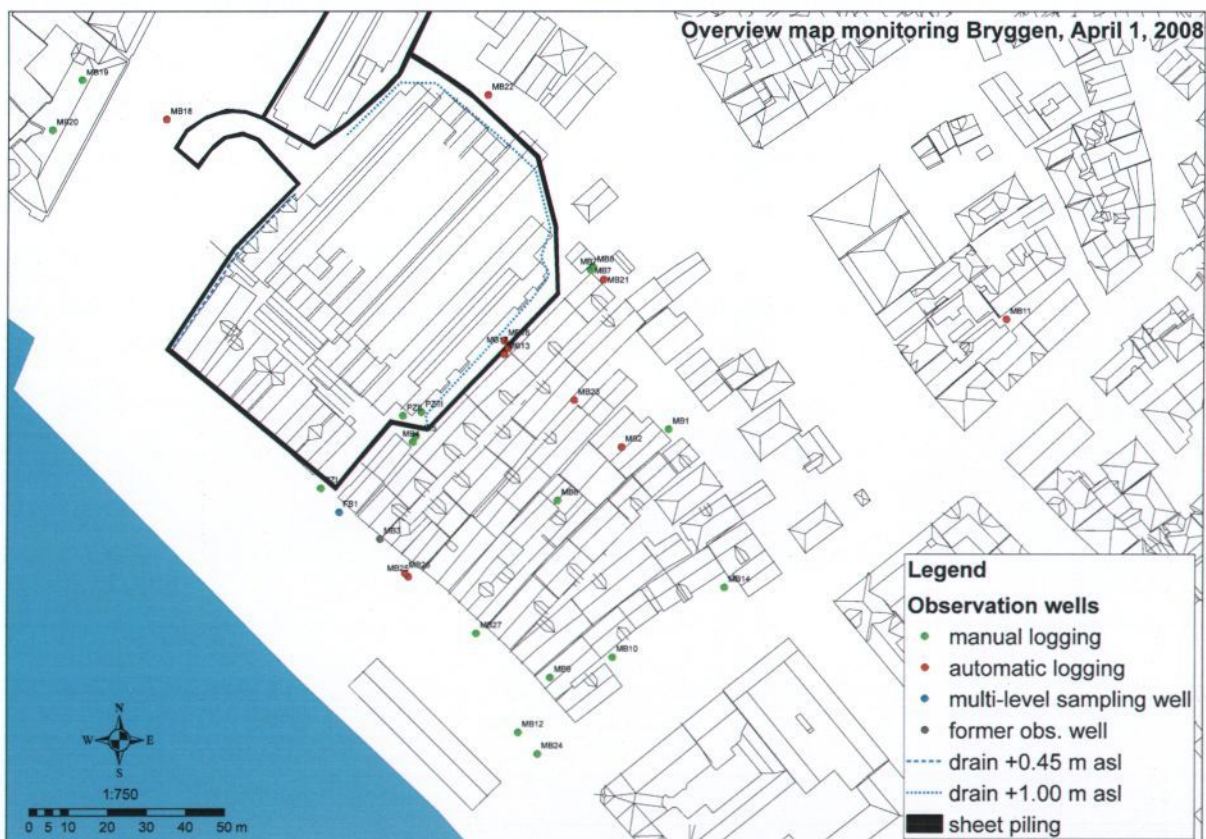


Figure 1: Map of Bryggen, showing the position of the different dipwells. The quay front is at the lower left corner of the map. Graphics: Hans de Beer.

The drillings are described in a number of reports by Rory Dunlop from NIKU (archaeology and state of preservation); Jann Atle Jensen from Multiconsult (geotechnical properties); Hans de Beer from NGU (hydrology) and Henning Matthiesen from The National Museum of Denmark (preservation conditions). The dipwells consist of a long tube, which is perforated at the lower one to several meters, to allow water to enter. The position and water intake of the different wells are described in Appendix 1 and a profile of the area is shown in Figure 2.

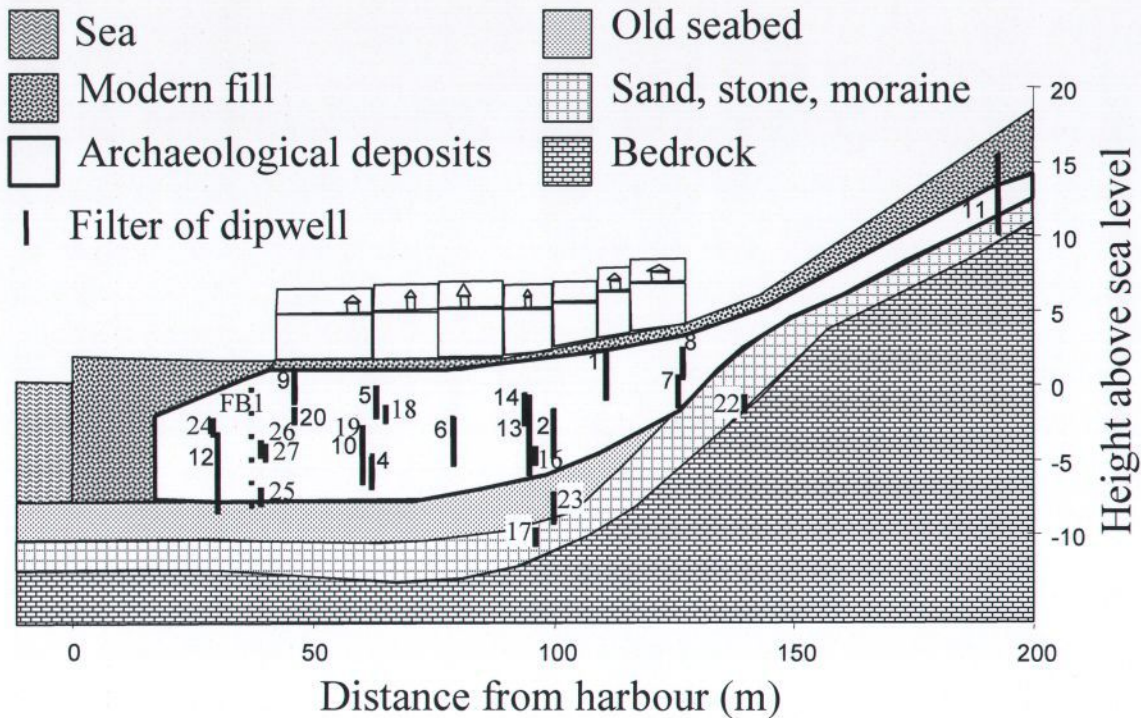


Figure 2: Profile perpendicular to the quay front showing the filters from the different dipwells on Bryggen. The depth and extent of the different soil strata is only sketched – in reality the depth to the natural deposits varies considerably across the area.

Water has been sampled from the dipwells on several occasions from 2002 to 2008. All sampling has been made by Multiconsult AS and NOTEBY, except for a partial sampling in April 2007, which was made by Hans de Beer, NGU.

The first sampling phases in 2002 showed problems with pollution by oxygen during the sampling, as described in Matthiesen (2003). A methodology has thus been developed to avoid these problems: The dipwells are emptied (purged) before the actual sampling to ensure that fresh water from the cultural layers is sampled. The purging takes place under argon gas flow to avoid oxygen uptake when the water trickles into the emptied dipwell. The water samples are filtered and conserved in the field (0.45 µm Gelman high capacity in-line filter) in order to distinguish between the dissolved and particulate content of the different species.

In 2008 pH, conductivity, oxygen content and temperature were measured in the field. Special attention was given to the samples for methane measurements – this gaseous analyte can easily escape during the sampling, so an in-line sampling directly into evacuated bottles was made, according to the instructions from the laboratory.

The samples were sent to the laboratory for a detailed groundwater analysis, covering pH, conductivity, alkalinity/bicarbonate, salt (sodium, chloride), nutrients (ammonium, nitrate, phosphate), redox active species (oxygen, sulphate, nitrate, nitrite, dissolved iron, dissolved manganese, sulphide, methane), and other major ions (calcium, magnesium, potassium). In the later sampling campaigns Eurofins in Denmark has made the analyses, as they offer this standard package with a good analytical quality and at a reasonable price.

Results

Observations made during the sampling and all results from the laboratory in 2008 are listed in Appendix 1. The full observation schemes and laboratory reports are available on request as .pdf files. A graphical presentation of the data from May 2008 is given in Figures 3-8, along with time series for the dipwells where there are multiyear data. Results from the first samplings (February to May 2002) are not presented here, as they are discussed in detail in Matthiesen (2002) and as the sampling was made in a slightly different way. No data are given for MB8 or MB21 as the dipwells were empty at the time of sampling. MB3 was removed because it had been placed through a sewer, and no dipwell has been appointed the name MB15. Other gaps in the data series are due to the concentrations being very low (in some cases even below the detection limit of the method), or because the parameters were not analysed in some of the sampling campaigns (which is then mentioned in the legend).

Salt:

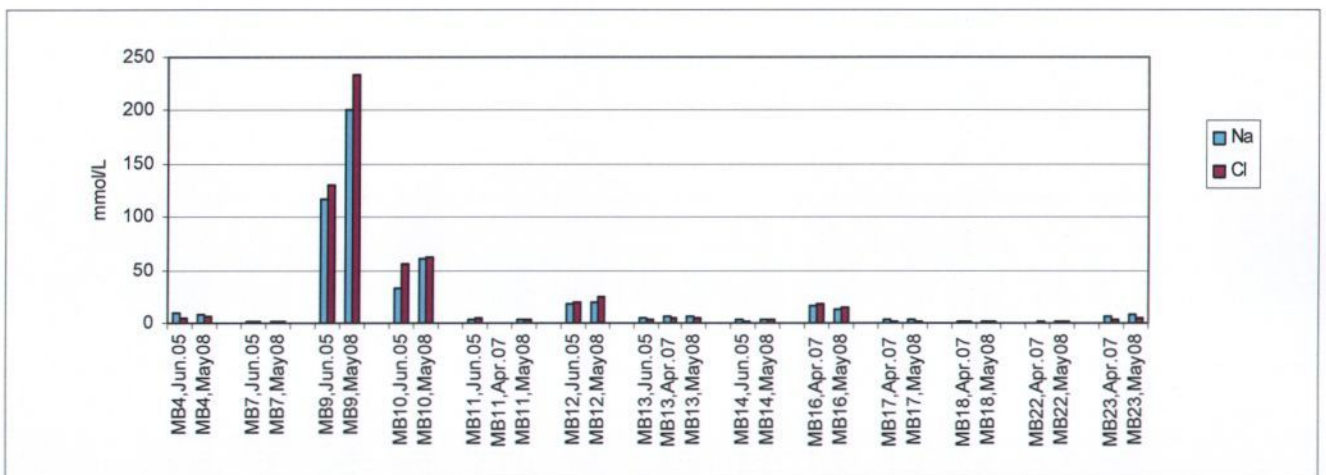
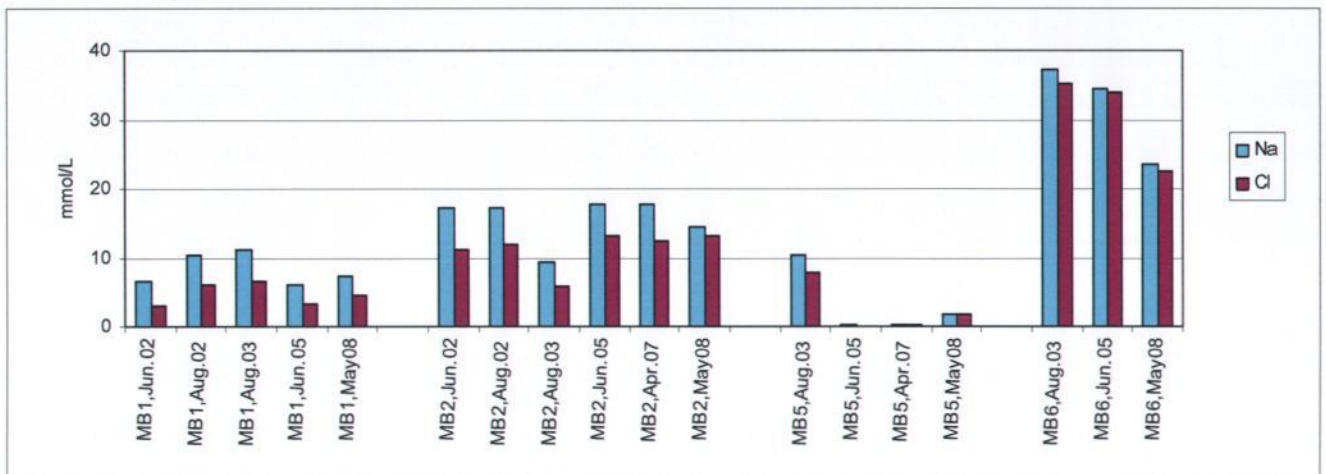
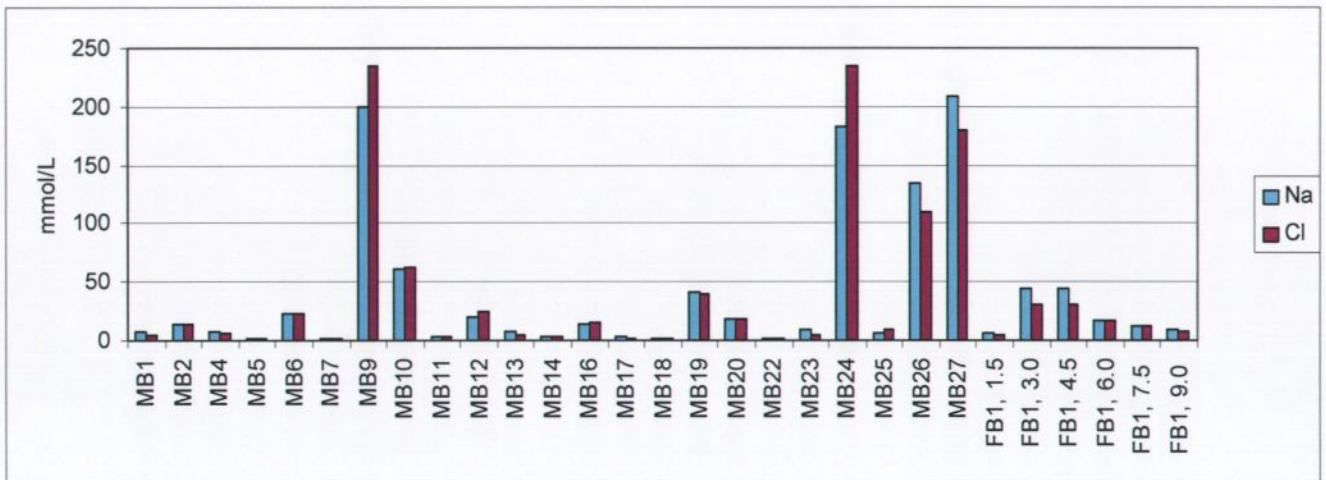


Figure 3: Concentrations of sodium (Na) and chloride (Cl) in the dipwells in May 2008 (upper diagram) and as time series (lower 2 diagrams). For results in mg/L the numbers in mmol/L must be multiplied by 22.99 for Na, and 35.45 for Cl.

Nutrients:

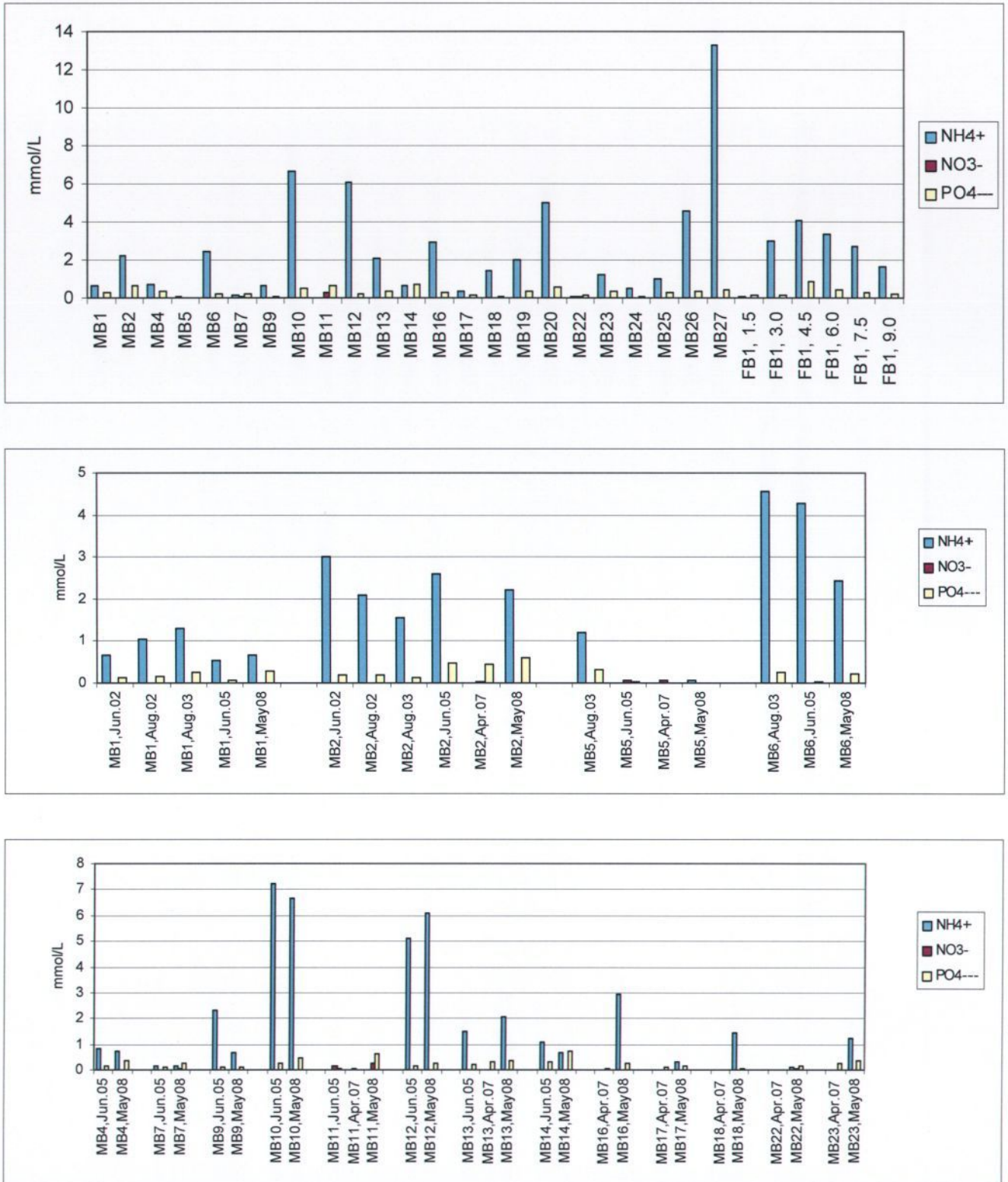


Figure 4: Concentrations of ammonium (NH₄⁺), nitrate (NO₃⁻) and phosphate (PO₄³⁻) in the dipwells in May 2008 (upper diagram) and as time series (lower 2 diagrams). Ammonium wasn't analysed in Apr. '07. For results in mg/L the numbers in mmol/L must be multiplied by 14.01 for nitrate and ammonium (to give mg N/L) and by 94.97 for phosphate (to give mg PO₄³⁻/L).

Oxidants:



Figure 5: Concentrations of different oxidants in the dipwells in May 2008 (upper diagram) and as time series (lower 2 diagrams). Oxygen wasn't analysed in May '07, and in May '08 there is a systematic pollution or bias of approximately 0.02 mmol/L. For results in mg/L the numbers in mmol/L must be multiplied by 32.00 for oxygen, 14.01 for nitrate (to give mg N/L), and by 96.06 for sulphate (to give mg SO₄²⁻/L)

Reduced species:



Figure 6: Concentrations of different reduced species in the dipwells in May 2008 (upper diagram) and as time series (lower 2 diagrams) – NH₄⁺ is shown in Figure 4. For results in mg/L the numbers in mmol/L must be multiplied by 54.94 for manganese, 55.85 for iron, 32.06 for sulphide (to give mg S/L), and by 16.04 for methane (to give mg CH₄/L). Sulphide wasn't analysed in Apr. '07, and in May '08 the results for MB2, MB9, MB12 and MB24 were reported as "too high" for the analytical method applied. Methane was only measured in August '03, June '05 and (with a dedicated sampling technique to avoid loss) in May '08. No sample was taken for methane or sulphide from FB1 (3.0 m) in May '08.

pH and bicarbonate:

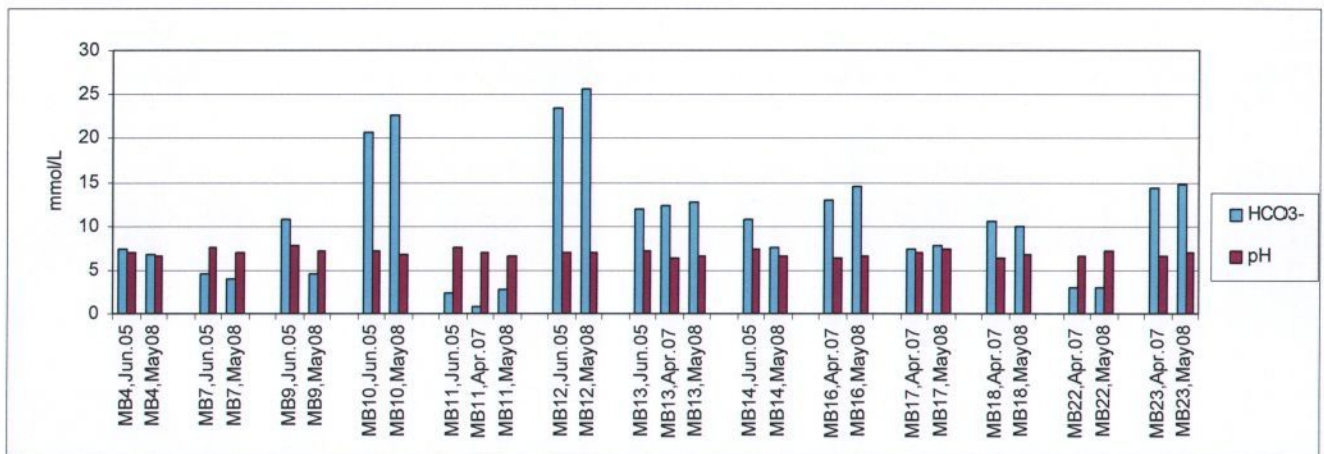
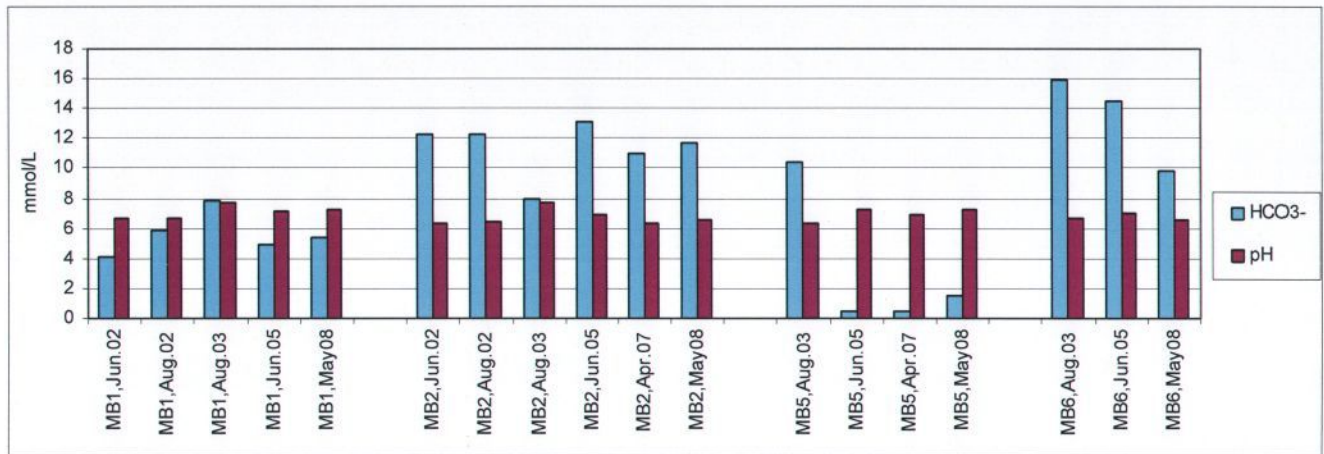
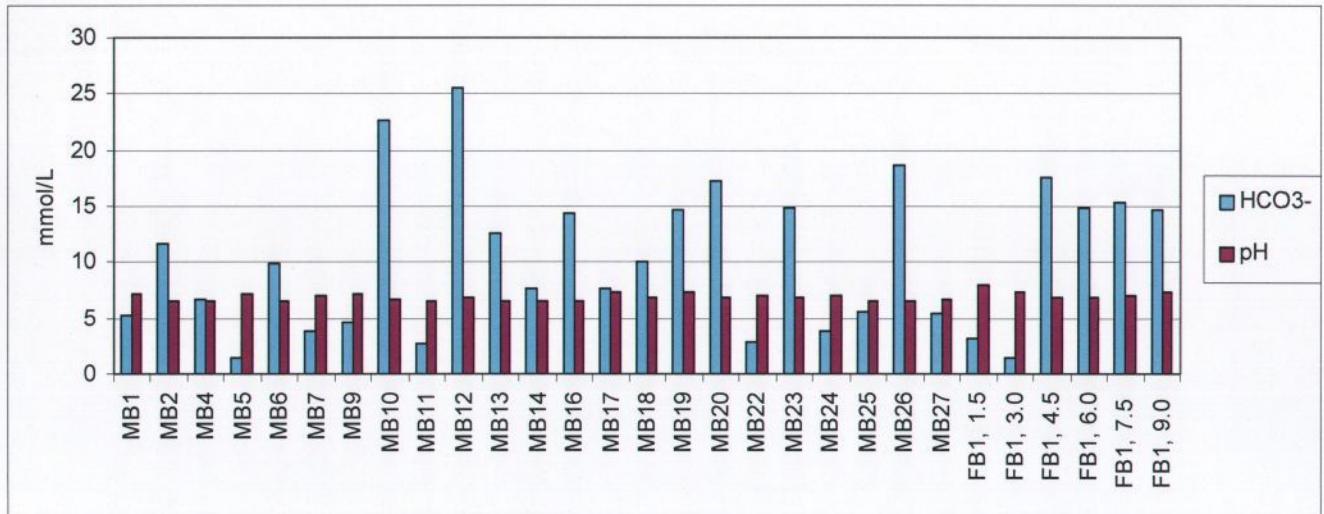


Figure 7: pH and bicarbonate in the dipwells in May 2008 (upper diagram) and as time series (lower 2 diagrams). pH is unitless, while the bicarbonate (HCO₃⁻) has the unit mmol/L.

Other major ions:

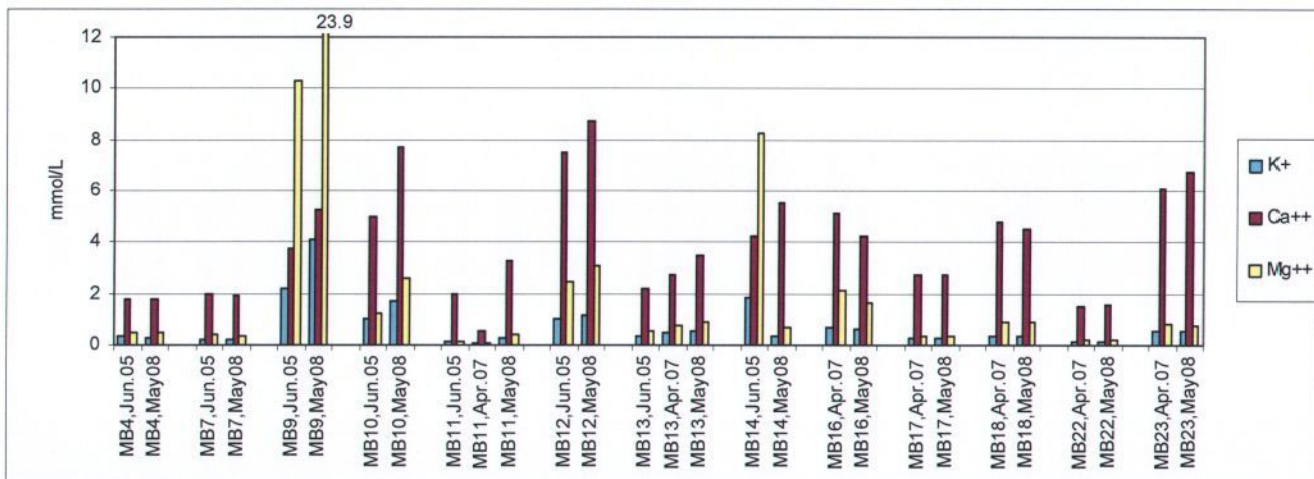
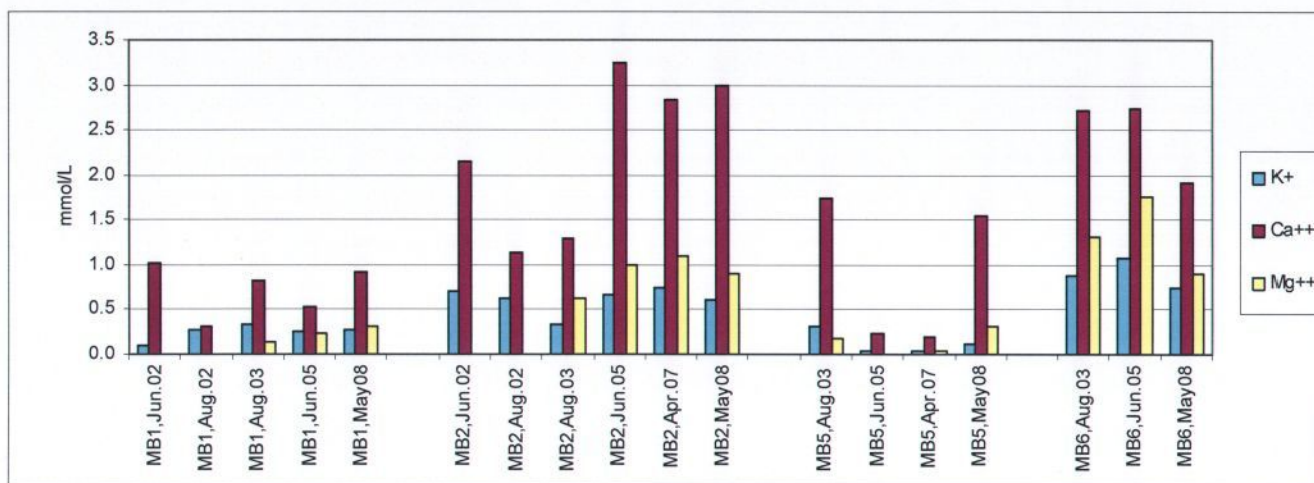
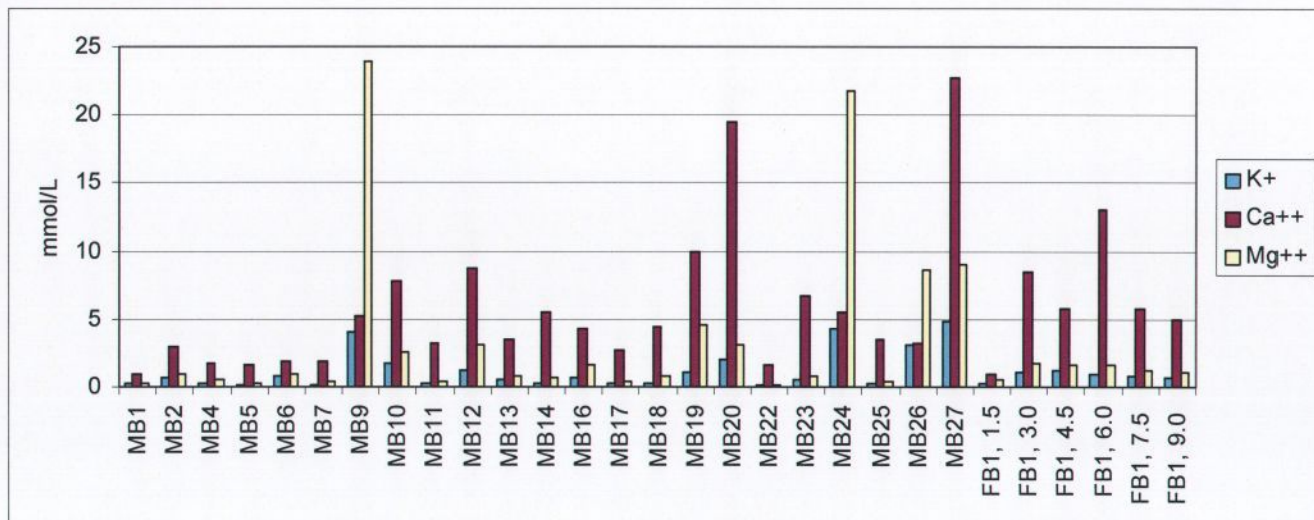


Figure 8. Concentrations of potassium (K⁺), calcium (Ca²⁺), and magnesium (Mg²⁺) in the dipwells in May 2008 (upper diagram) and as time series (lower 2 diagrams). For results in mg/L the numbers in mmol/L must be multiplied by 39.10 for potassium, 40.08 for calcium, and by 24.31 for magnesium. Magnesium wasn't analysed in June and August '02.

Discussion

The ground water sampling is a cornerstone in the monitoring programme at Bryggen. After the last major sampling campaign in 2005 it was demonstrated how the groundwater chemistry reflects the preservation conditions (Matthiesen, 2008b; Matthiesen, 2006) and the picture was refined by a partial sampling in 2007 (de Beer & Matthiesen, 2008). The first samples were taken in 2002, and with the new sampling in 2008 there are now time series of 7 years for some of the dipwells. This makes it possible to see whether the ground conditions are stable or changing over time.

Furthermore, the increased number of dipwells in the area has made it possible to evaluate whether the first models of the groundwater formation and -chemistry are still valid or need to be modified.

Analytical quality

The comprehensive analyses of the water samples allow us to make different checks on the analytical quality: For instance, all water samples must be electrically neutral – this is checked by summing up all the positive ions and all the negative ions to see if the positive and negative charge is equal. From the concentrations of the different ions it is also possible to calculate a theoretical conductivity and compare this with the measured conductivity. Finally, there are several chemical “rules” that for instance allow us to compare the results for all redox active species.

These tests have been made for all the dipwells, and generally show that the results are consistent, giving good confidence in the data. However, there are also a few exceptions where there is some doubt about the quality of some results:

- There is a large electrical imbalance for dipwells MB5, 14, 19, 20, 27 and FB1 (3 and 6 m). It hasn't been proved yet what is the cause of this imbalance, but it can for instance occur if the samples for some of the species are oxidised or if calcium carbonate (or other solids) precipitate before the analysis takes place.
- The oxygen measurements in 2008 were made inline, but there still seems to be a systematic pollution (or a blind value of the instrument) of approximately 0.02 mmol/L (0.5 mg/L)
- The methane results in 2008 are much higher than in earlier sampling campaigns. Methane (CH₄) is difficult to sample because it escapes very easily as a gas, but in 2008 special attention was given to the procedure, using an in line sampling method where water was sampled directly into evacuated bottles. The 2008 results are thus considered realistic, whereas the earlier results are considered too low.
- The multilevel well FB1 consists of 6 piezometers at different depths, connected to the surface by a thin tube. Sampling is made by suction, which may influence the results for gaseous components (such as oxygen, sulphide and methane). Sampling may be slow, which means that the water temperature may also be biased (i.e. the water has sufficient time to equilibrate its temperature with the surroundings before the temperature is measured).
- The high Mg²⁺ content reported for MB14 in June '05 has earlier been questioned (Matthiesen, 2006), and the renewed sampling in 2008 seems to verify that the 2005-results were unrealistically high (Figure 8). Furthermore, the possible exchange of Cl⁻ and NH₄⁺ contents in dipwells MB6 and 7 in 2005 (discussed in Matthiesen, 2006) has now been verified.
- The correlations between the species NH₄⁺ - K⁺, Ca²⁺ - HCO₃⁻, and NH₄⁺ - HCO₃⁻ observed for the 2005 samples (Matthiesen, 2008b) are also present for the 2008 samples (not shown).

Temporal variation

Temporal variation in the chemical composition of ground water can have different time scales: Short term variations (daily or weekly) can for instance be due to dynamic conditions where the dipwell is directly influenced by precipitation or tide level. Medium term variation can for instance be due to seasonal changes. Finally, long term variations (over several years) may indicate a more permanent change in the conditions at the site. The difficult task is of course to differentiate between these types of variations and find out if there is a permanent change in the preservation conditions at Bryggen.

The temporal variation is best observed with automated loggers that make continuous measurements of different analytes. Between 2003 and 2005 an automated oxygen logger was used, that was moved between dipwells MB1, 2, 3, 5, 6, and 7 (Matthiesen, 2005). This showed that there was a fast (daily) variation in the oxygen content and temperature of dipwells MB3 and MB5, depending on the precipitation. This is interpreted as fresh rainwater flushing through the deposits around the logger. In the period 2006-2008 Hans de Beer from NGU installed automated loggers for water table and temperature in 12 dipwells (MB2, 7, 11, 13, 16, 17, 18, 21, 22, 23, 25 and 26). Out of these MB11, 21 and 26 show short term (daily) temperature variation of a few degrees (de Beer, 2008) which indicates dynamic conditions around the logger. MB13 and 16 show daily temperature variation of a smaller magnitude.

As for the medium term variation, all loggers show seasonal variation in the temperature, which vary between 1 and 4 degrees over a whole year in the different dipwells. It is not possible to evaluate any long term variation from the loggers yet, as they have only been installed for approximately 1½ years by now.

Regarding the chemical analysis, repeated groundwater sampling has been made in dipwells MB1, 2, 4, 5, 6, 7, 9, 10, 11, 12, 13, 14, 16, 17, 18, 22 and 23 (Figure 3-8, lower diagrams). Dipwells MB1 and MB2 were sampled already in 2002, and the rest of the dipwells were included in the program as they were installed. Most of the dipwells show a relatively low variation in the water composition over time, even if the number of samplings is not yet sufficient to prove that the conditions are “stable”. On the other hand, MB5, 9 and 11 show a distinct variation in the water composition, and some variation is observed in MB6 and 2 as well:

MB5 changes radically over time: In August 2003 there are anoxic conditions (Figure 5 + 6) and the salt and nutrient contents are similar to what is found in most dipwells. In June 2005 and April 2007, on the other hand, there are oxic conditions with high nitrate concentrations and a very “diluted” sample similar to rainwater. In May 2008 there are anoxic conditions again, and with a higher salt content. This picture fits well with the observations from loggers, which show very dynamic conditions where the water type changes weekly or daily depending on the amount of precipitation (Matthiesen, 2005).

MB9 changes regarding the salt content, which is almost double as high in May 2008 compared to June 2005 (Figure 3). Again this is a dynamic dipwell very close to the soil surface, where the actual composition of the water will reflect the mixture of seawater and freshwater in the small pond that is present around the dipwell inside building VIIIa. A study by NIVA using automated

conductivity loggers showed how the salinity at the bottom of the dipwell varied between 8 and 17 PSU within just a few days (Golmen, 2005).

MB11 shows a high variation in the SO_4^{2-} , HCO_3^- , Ca^{2+} , NO_3^- and Fe^{2+} content (Figure 4-8), and the conditions vary between oxic to slightly reducing. This fits well with results from the automated logger showing dynamic conditions where the temperature varies on a daily basis depending on the precipitation.

There is thus a good correspondence between the results for the chemical analysis and the automated loggers, and for MB5, 9 and 11 the variations are due to dynamic conditions on a daily timescale. All of these dipwells are placed in what we may call the “outskirts” of the cultural deposits (MB11 at the back of Bryggen, MB9 in the top of the deposits at the harbour front, and MB5 right next to the sheet pile).

Some variation is also indicated by the chemical analyses in dipwells MB6 and 2. Here the automated loggers only show quite small (less than 0.5 degrees) short term variations in the temperature.

At MB2 there is a temporary change in August '03 with a decrease in Na^+ , Cl^- , NH_4^+ , Ca^{2+} , K^+ and HCO_3^- and an increase in pH and SO_4^{2-} . Some NO_3^- is found as well. It is difficult to relate this to a specific event near MB2, but in principle an intrusion of rainwater could give a similar fingerprint, except maybe the increase in pH.

At MB6 there is a 30-50% decrease in the content of Na^+ , Cl^- , NH_4^+ , Ca^{2+} , and HCO_3^- , and an increase in SO_4^{2-} and Fe^{2+} in 2008 compared to earlier measurements. This is about the same picture as seen in MB2 in August '03. The change is a bit surprising as MB6 has hitherto been considered representative for the most stable or stagnant conditions at Bryggen. However, only 3 samples have been analysed until now and it is too early to say if this is a permanent change. It may even be the same temporary event as observed at MB2 that has now moved through the deposits and reached MB6.

Overall the data do not indicate any systematic deterioration or improvement in the preservation conditions during the monitoring period for the dipwells investigated. It must be emphasized, however, that we do not yet have multiple samples or logger data from all dipwells in the Bryggen area.

Spatial variation

The spatial variation in the groundwater composition is shown in Figure 9 (major ions) and Figure 10 (redox sensitive species), where the data are projected onto a vertical profile perpendicular to the quay front. The spatial variation in the horizontal plane is shown in Figure 11.

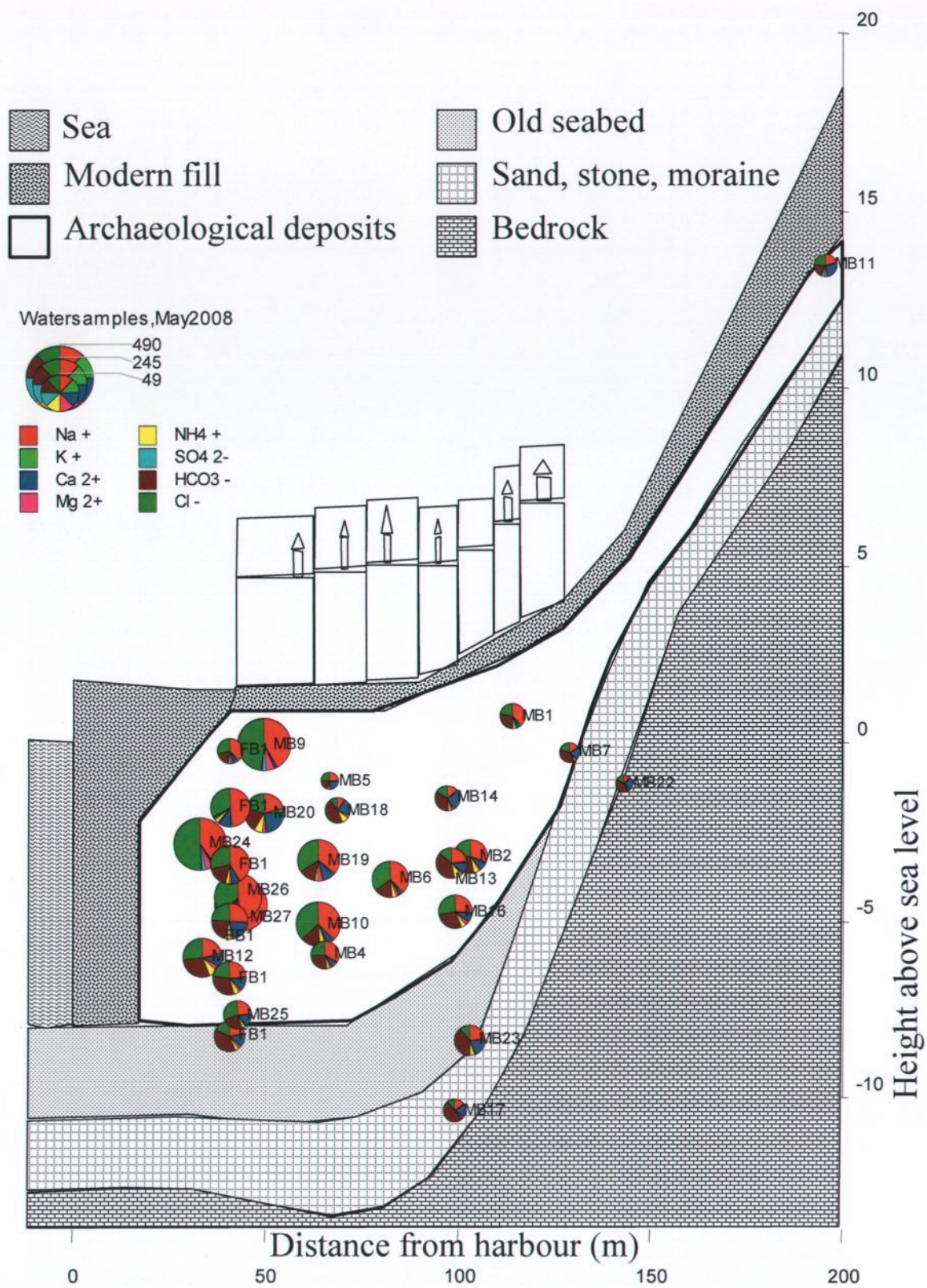


Figure 9: Major ions from water samples, May 2008. Unit is mmol/L (not meq/L). The diameter of the circle represents the total amount of ions on a logarithmic scale – thus MB9 contains 485 mmol/L compared to only 8 mmol/L at MB5. The depth and extent of the different soil strata is only sketched – in reality the depth to the natural deposits varies considerably across the area.

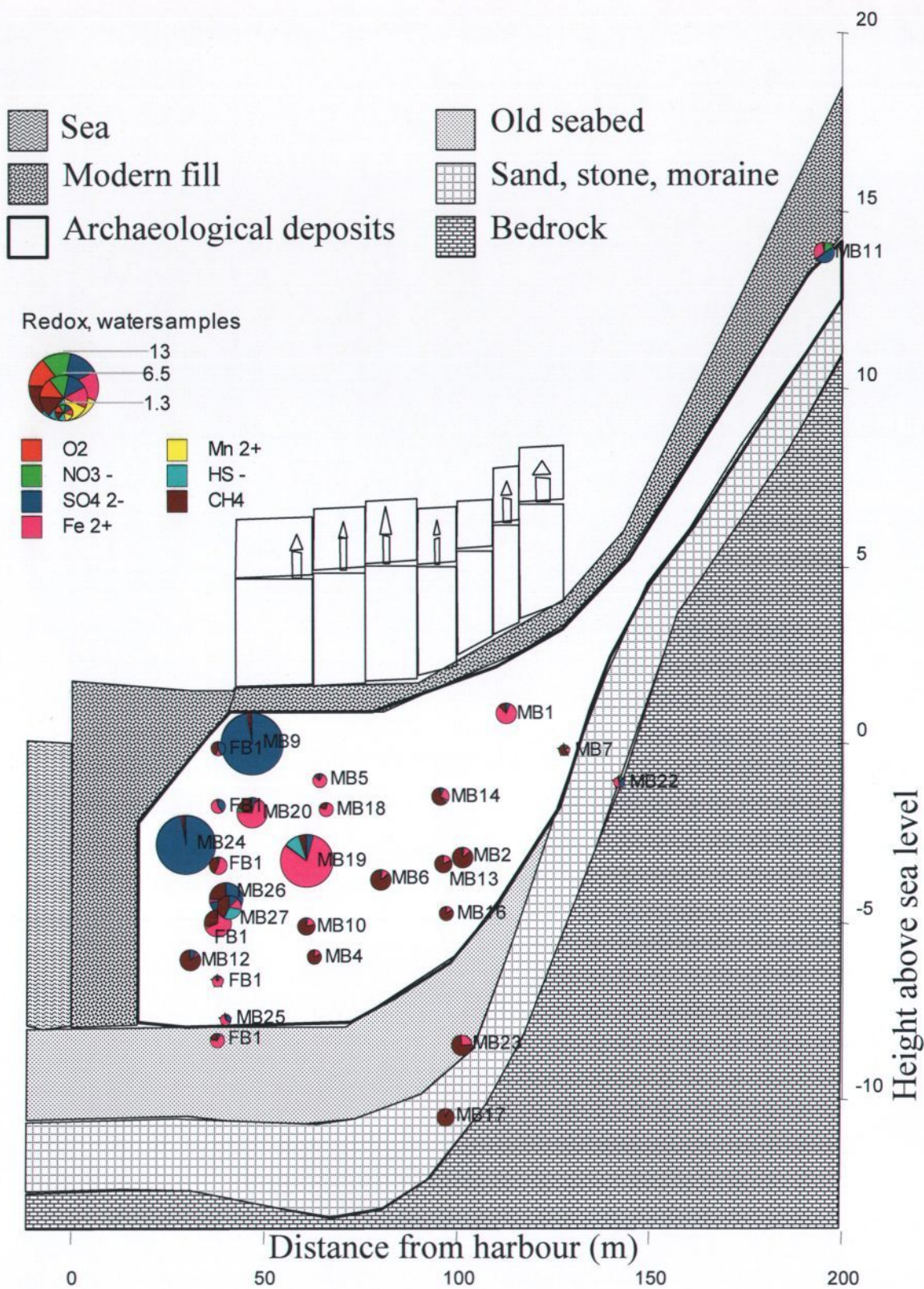


Figure 10: Redox sensitive species in water samples, May 2008. Unit is mmol/L (not meq/L). The area of the circle represents the total amount of redox sensitive species. The depth and extent of the different soil strata is only sketched – in reality the depth to the natural deposits varies considerably across the area.

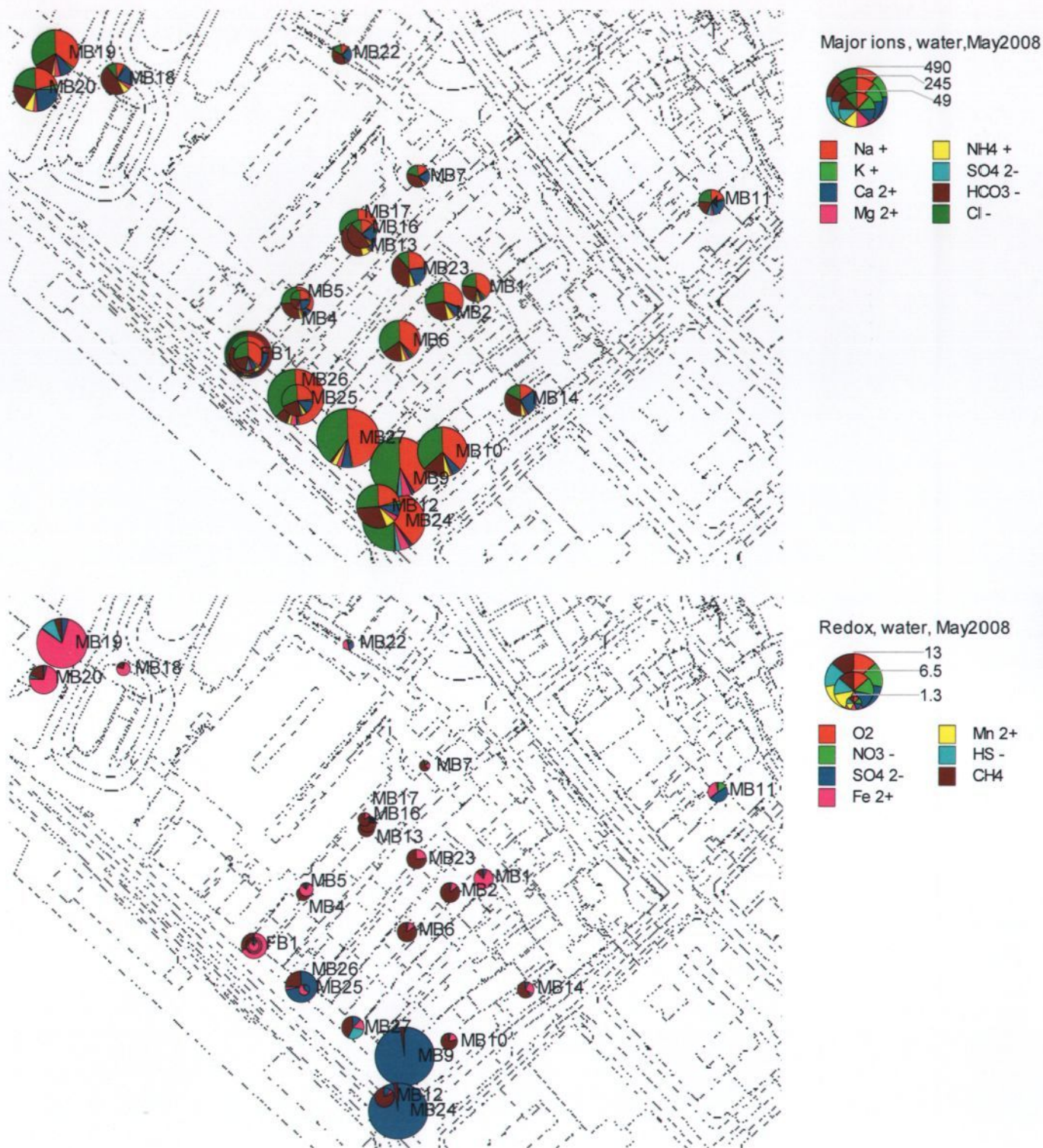


Figure 11: Horizontal distribution of major ions (upper map) and redox sensitive species (lower map) in groundwater samples from May 2008.

The spatial distribution of different chemical species in the groundwater has already been discussed in previous papers (de Beer & Matthiesen, 2008; Matthiesen, 2008b; Matthiesen, 2006). Here a preliminary “conceptual” model for the groundwater-chemistry and –formation based on the mixing of three types of water (rainwater, seawater and stagnant water) was presented. However, the model was based on a smaller number of dipwells, which were mainly placed within the archaeological

deposits. Since then more dipwells have been installed beneath the archaeological deposits and at the harbour front (de Beer & Matthiesen, 2008; Matthiesen, 2008a). This leads to a minor adjustment of the conceptual model, as we may now also include the natural deposits underneath with a contribution of groundwater from the bedrock/natural deposits (Figure 12).

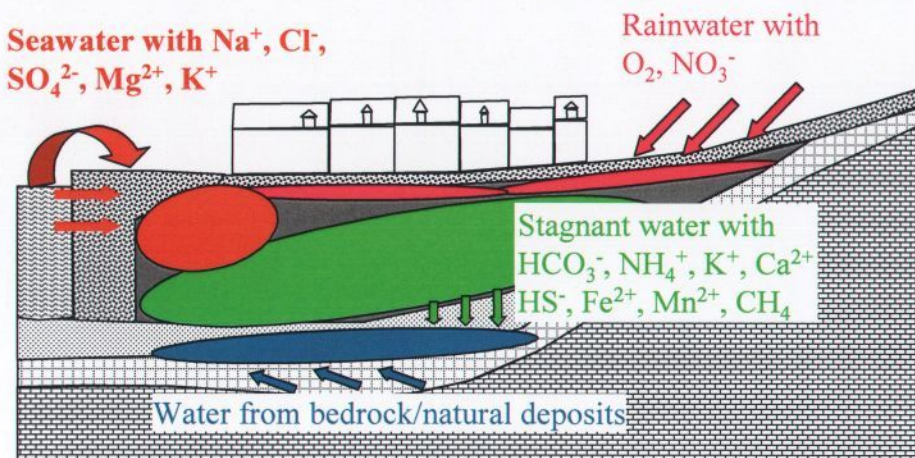


Figure 12: Conceptual model of the groundwater flow and –development at Bryggen. Updated from Matthiesen (2008b)

The **seawater** influence is dominant in MB9, MB24, MB26, MB27 and to some extent also FB1 (1.5, 3.0 and 4.5), all placed in the upper soil layers at the harbour front. The water in the dipwells is characterised by a high (and probably varying) salt content, including the ions Na^+ , Cl^- , SO_4^{2-} , Mg^{2+} and K^+ . These dipwells, and the possible effect of sulphate reduction at the quay front, are discussed in detail in Matthiesen (2008a). The preservation conditions are considered poor in this area due to sulphate reduction, but the exact extent needs to be better investigated, amongst others by conductivity loggers and frequent water sampling for Cl^- and SO_4^{2-} analysis.

The **rainwater** influence is most clearly seen in MB5 and MB11 (both showing very dynamic conditions) and to some extent also MB7 and MB22, but rainwater will also “dilute” the stagnant water when it penetrates into the deposits. The rainwater contains some oxygen and NO_3^- , which may oxidise a small amount of organic material in the soil. MB11 also contains surprisingly high concentrations of sulphate, which must have a non-marine origin, considering the position of MB11 high above the sea.

The **stagnant water** is found in its “purest” form in MB6, but also MB1, MB2, MB4, MB7, MB10, MB12, MB13, MB14, MB16, MB18, MB19, MB20 and FB1 (6.0 and 7.5) are considered belonging to this group, showing different degrees of dilution by rainwater. MB26 and MB27 have some of the same characteristics, but are diluted by seawater. The water in the dipwells is characterised by Ca^{2+} , HCO_3^- , NH_4^+ , CH_4 as well as other reduced species. The preservation conditions are considered good in this region.

Finally, the “**natural deposits**” are reached in MB17, MB22, MB23, MB25 and FB1 (9.0). The chemical “signature” found in these dipwells is quite similar to what is found in the stagnant water above, only is it more diluted. This may be explained by a downwards flow of the groundwater from the archaeological deposits and dilution by water with a low ion content running through the rock /natural deposits (de Beer, 2008). The downward flow direction means, that the groundwater from the natural deposits will hardly influence the preservation conditions in the overlying archaeological deposits.

The depth distribution of selected parameters: bicarbonate (HCO_3^-) and methane (CH_4) is shown in Figure 13. Both species may come from the decomposition of organic material.

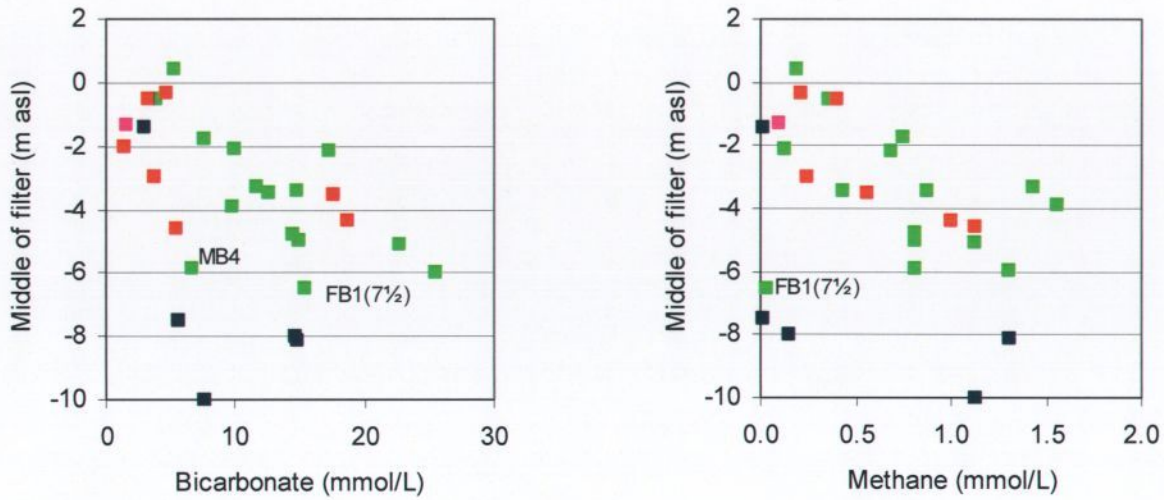


Figure 13: Depth distribution of bicarbonate (left) and methane (right) in May 2008. The different colours refer to dipwells influenced by seawater, rainwater, stagnant water, and natural deposits. MB4 may be influenced by an increased ground water flow next to the sheet pile, and the methane measurements in FB1 may be biased by the sampling procedure (sampling is made by suction in this multi-level well, which may give a loss of the volatile methane)

The increasing concentration of bicarbonate with depth has earlier been discussed in de Beer & Matthiesen (2008). It indicates 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. In the natural sediment (blue points) there is an increased mixing with diluted (possibly younger) groundwater from the permeable sandy sediments.

As for the methane, there has been special focus on the sampling procedure in 2008, resulting in significantly higher values than at earlier sampling campaigns (Figure 6). Methane production takes place in the most reduced zones, where all other oxidants have been used up. It is either linked to fermentation of acetate ($\text{CH}_3\text{COOH} \rightarrow \text{CH}_4 + \text{CO}_2$) or reduction of CO_2 by hydrogen ($\text{CO}_2 + \text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$). There is a good correlation to the depth of the dipwell, except for the dipwells placed in the natural deposits. Methane may migrate upwards as a gas, but the compact nature of the archaeological deposits allows high concentrations of $> 1\text{mmol/L}$ to build up.

The horizontal distribution of the major ions (as shown in Figure 11, upper map) indicates that the highest salt concentrations are found at the quay front towards the south-eastern side. As for the redox sensitive species (Figure 11, lower map) it is striking that very high concentrations of Fe^{2+} are found at MB19 and 20 on the western side of the hotel. These dipwells are placed underneath a building (Slotsgaten 1), which was built on concrete piles in 1916. In 2005 additional piles (of steel) were installed during restoration of the building, and a monitoring program was initiated. At this

point it cannot be excluded that the increased Fe^{2+} concentration are connected to corrosion of the steel piles, but we have no data from before the restoration to confirm this theory.

Dipwells MB19 and MB20 also stand out in terms of the temperature of the groundwater (Appendix 1), which was 17.8°C in MB19 and 16.3°C in MB20 at the time of sampling. For comparison the other dipwells on Bryggen showed temperatures of 8-13°C (FB1 showed temperatures of 14-16 °C, but this could be due to a slow sampling). The building on Slotsgaten 1 has a cellar down to 0 m asl and the high temperature in the dipwells is probably due to heat transport from the cellar and downwards. The exact effect on the preservation conditions cannot be estimated yet.

Conclusion and recommendations

A comparison between 28 groundwater samples from Bryggen has been presented.

- The results from the chemical analyses are generally consistent and considered of high quality, showing that the sampling methodology and analyses are adequate
- The results have confirmed and refined the earlier established conceptual model for groundwater chemistry and -formation
- The preservation conditions at Bryggen are considered good, except in the upper soil layers at the harbour front and near to the sheet pile. The preservation conditions beneath Slottsgaten 1 need to be further evaluated.
- There are no signs of changing preservation conditions during the monitoring period, as only minor temporal variations are seen when comparison is made to samples from 2002-2007

Future work with groundwater sampling should include

- The data should be further evaluated in terms of a combined hydrological-geochemical model
- Logging of the salinity and frequent sampling for chloride/sulphate content should be made in dipwells at the harbour front to further evaluate the extent of sulphate reduction
- Logging of the redox conditions (oxygen content) should be made in dipwells near the sheet pile. This will provide reference data to evaluate the effect when the drainage from the hotel is stopped
- Logging of the temperature could be relevant beneath Slottsgaten 1, in order to document the effect of building upon cultural deposits
- Special attention should be given to MB6 to see if the changed composition in 2008 is only temporary.
- New samples should be taken in all dipwells in 3-5 years time

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Appendix 1

Results from chemical analysis and observations made during sampling of water 19-29 May 2008. Results are given by the laboratory in mg/L, but have been recalculated to mmol/L using the molar weights given in the table.

Reports from the laboratory (Eurofins) and the water sampler (Multiconsult) are available upon request.

	MB1	MB2	MB4	MB5	MB6	MB7	MB9	MB10	MB11	MB12	MB13	MB14	MB16	MB17
x	297519.751	297507.633	297454.210	297454.986	297491.299	297499.567	297489.592	297505.547	297606.297	297481.388	297477.469	297534.297	297477.481	297478.496
y	6701336.513	6701331.949	6701333.198	6701334.655	6701318.164	6701377.659	6701272.658	6701277.855	6701364.945	6701258.540	6701355.873	6701295.773	6701359.292	6701357.441
Distance to harbour (m)	111	100	62	63	79	126	46	60	193	30	95	94	96	96
Dipwell top (m asl)	2.78	2.18	1.62	1.67	1.62	4.21	1.65	1.42	16.91	1.12	2.05	2.26	2.14	2.13
Filter top (m asl)	1.90	-1.80	-4.88	-0.30	-2.38	0.46	0.65	-3.58	14.81	-3.45	-0.95	-0.74	-4.26	-9.49
Filter bottom (m asl)	-1.10	-4.80	-6.88	-2.30	-5.38	-1.54	-1.35	-6.58	9.81	-8.45	-5.95	-2.74	-5.26	-10.49
Natural deposit (m asl)	-1.00			-9.35	-6.60	-1.80		-6.38	11.00	-8.28	-6.10	-4.09		
Rock (m asl)				-8.75	-2.50			-10.28	9.40					
Sampling date	20-05-08	20-05-08	20-05-08	20-05-08	20-05-08	19-05-08	20-05-08	20-05-08	26-05-08	20-05-08	19-05-08	27-05-08	19-05-08	19-05-08
Water level (m asl)	2.10	1.12	0.22	0.31	1.06	0.61	0.29	0.47	11.56	-0.15	0.47	1.35	0.20	0.25
Volume pumped (L)	12	20	4	4	5.00	4.00	6.00	12.00	14.00	17.00	25.00	8.00	14.00	45.00
Parameter	weight													
Unit:	mmol/L													
Na+	7.39	14.35	8.26	1.78	23.49	1.70	200.09	60.90	3.09	19.57	7.39	3.26	13.92	2.48
K+	0.28	0.61	0.28	0.11	0.74	0.19	4.09	1.71	0.25	1.18	0.51	0.33	0.61	0.28
Ca++	0.92	2.99	1.77	1.55	1.92	1.92	5.24	7.73	3.24	8.73	3.49	5.49	4.24	2.74
Mg++	0.31	0.91	0.49	0.31	0.91	0.35	23.86	2.59	0.39	3.09	0.86	0.70	1.65	0.37
Mn++	0.03	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.03	0.00	0.01	0.02	0.01	0.01
Fe++	1.31	0.16	0.15	0.64	0.20	0.08	0.13	0.27	0.57	0.11	0.16	0.29	0.13	0.07
NH4+	0.67	2.22	0.72	0.07	2.44	0.14	0.67	6.65	0.01	6.10	2.05	0.67	2.94	0.33
Cl-	4.51	13.26	6.49	1.72	22.57	2.17	234.11	62.05	3.67	24.26	4.51	3.67	14.95	1.89
SO4--	0.11	0.06	0.03	0.06	0.09	0.03	12.49	0.05	0.77	0.17	0.03	0.10	0.03	0.00
NO2-	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO3-	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00
P-tot	0.28	0.61	0.36	0.02	0.22	0.24	0.10	0.48	0.61	0.23	0.36	0.74	0.27	0.16
HS-	0.00	too high	0.00	0.02	0.01	0.01	too high	0.00	0.00	too high	0.01	0.04	0.02	0.00
HCO3-	5.33	11.72	6.72	1.49	9.82	3.88	4.61	22.62	2.79	25.57	12.62	7.60	14.42	7.69
F-	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
O2	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.04	0.02	0.01	0.02	0.02	0.01
CH4	0.19	1.43	0.81	0.09	1.56	0.36	0.21	1.12	0.00	1.31	0.87	0.75	0.81	1.12
pH	7.2	6.6	6.6	7.2	6.5	7	7.2	6.7	6.5	6.9	6.6	6.5	6.6	7.3
Conductivity (mS/m)	60	137	97	22	236	198	1670	584	55	329	164	30	282	66
Dry weight (mg/L)	580	1300	810	240	1800	360	18000	4700	2600	920	1500	530		
Colour	sort/brun	0 blank/grålig	sort/brun	sort/brun	sort/brun	brun/grå	Sort	sort	sorte partikler	sort	brun	brun	gul, sorte part.	grå m hvide partikler
Temperature (°C)	8.7	8.7	8.9	8.7	8.9	8.5	8.3	9.7	9.3	9.8	12.6	11	12.4	11.4
Comments	H2S lugt	hoj H2S	m sand/silt	m. partikler	H2S lugt	m. partikler	H2S lugt	0 lugt af fisk	H2S lugt	H2S lugt	H2S lugt	H2S lugt	H2S lugt	svag H2S lugt
Sum cations (meq/L)	13.49	25.32	14.10	6.99	32.73	6.75	263.32	90.48	11.83	50.71	19.00	17.24	29.52	9.46
Sum anions (meq/L)	10.36	25.72	13.63	3.38	32.81	6.43	263.82	85.26	8.87	50.40	17.57	12.25	29.73	9.75
Diff cat-an	3.13	-0.40	0.47	3.61	-0.09	0.32	-0.50	5.23	2.96	0.31	1.43	4.99	-0.21	-0.29
Relativ diff (%)	13%	-1%	2%	35%	0%	2%	0%	3%	14%	0%	4%	17%	0%	-2%

	MB18	MB19	MB20	MB22	MB23	MB24	MB25	MB26	MB27	FBI, 1.5	FBI, 3.0	FBI, 4.5	FBI, 6.0	FBI, 7.5	FBI, 9.0
x	297390.821	297369.305	297361.722	297473.095	297495.436	297486.335	297453.172	297452.34	297470.672	297435.437	297435.437	297435.437	297435.437	297435.437	297435.437
y	6701416.415	6701426.534	6701413.659	6701422.672	6701344.008	6701252.996	6701298.498	6701299.369	6701283.982	6701315.099	6701315.099	6701315.099	6701315.099	6701315.099	6701315.099
Distance to harbour (m)	65	60	46	140	100	29	39	39	40	37	37	37	37	37	37
Dipwell top (m asl)	2.9	2.54	1.24	4.67	1.98	1.22	1	0.97	0.93	1	1	1	1	1	1
Filter top (m asl)	-1.58	-2.90	-1.65	-0.88	-7.12	-2.46	-6.96	-3.86	-4.07	-0.50	-2.00	-3.50	-5.00	-6.50	-8.00
Filter bottom (m asl)	-2.58	-3.90	-2.65	-1.88	-9.12	-3.46	-7.96	-4.86	-5.07	-0.50	-2.00	-3.50	-5.00	-6.50	-8.00
Natural deposit (m asl)	-2.90	-2.50	-2.50	0.75	-5.50		-8.25			-8.40	-8.40	-8.40	-8.40	-8.40	-8.40
Rock (m asl)	-3.90			-2.55											
Sampling date	20-05-08	29-05-08	29-05-08	19-05-08	28-05-08	20-05-08	26-05-08	26-05-08	28-05-08	29-05-08	29-05-08	29-05-08	29-05-08	29-05-08	29-05-08
Water level (m asl)	0.27	2.24	-0.94	0.46	0.34	0.16	0.22	0.14	-0.57						
Volume pumped (L)	6.00	13.00	7.00	20.00	45.00	25.00	14.00	14.00	9.00						
Parameter weight															
Unit: mmol/L															
Na ⁺	2.04	41.32	18.70	1.04	8.70	182.69	6.52	134.84	208.79	6.52	43.50	43.50	17.40	12.18	8.70
K ⁺	0.31	1.02	1.99	0.15	0.51	4.35	0.28	3.07	4.86	0.31	1.10	1.23	0.90	0.77	0.66
Ca ⁺⁺	4.49	9.98	19.46	1.60	6.74	5.49	3.49	3.24	22.70	0.97	8.48	5.74	12.97	5.74	4.99
Mg ⁺⁺	24.31	4.53	3.13	0.20	0.78	21.81	0.45	8.64	9.05	0.53	1.81	1.56	1.65	1.19	1.07
Mn ⁺⁺	0.02	0.10	0.09	0.01	0.01	0.00	0.01	0.00	0.01	0.00	0.03	0.02	0.05	0.02	0.02
Fe ⁺⁺	0.52	7.88	2.33	0.30	0.43	0.04	0.38	0.11	0.34	0.10	0.41	0.63	1.70	0.29	0.45
NH ₄ ⁺	1.44	2.00	4.99	0.08	1.22	0.49	1.00	4.60	13.31	0.04	2.99	4.10	3.38	2.72	1.66
Cl ⁻	2.23	39.49	18.62	1.35	4.23	234.11	8.74	110.00	180.52	5.08	31.03	31.03	16.64	11.56	7.33
SO ₄ ⁻⁻	0.03	0.48	0.12	0.23	0.00	11.45	0.19	2.81	0.35	0.36	0.28	0.07	0.06	0.05	0.07
NO ₂ ⁻	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NO ₃ ⁻	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
P-tot	0.07	0.39	0.55	0.17	0.36	0.06	0.30	0.36	0.42	0.12	0.12	0.87	0.42	0.32	0.22
HS ⁻	0.00	1.00	0.08	0.01	0.01	too high	0.00	0.08	0.66	0.00	no sample	0.01	0.00	0.00	0.00
HCO ₃ ⁻	10.01	14.73	17.21	2.92	14.78	3.80	5.57	18.68	5.41	3.25	1.45	17.54	14.86	15.34	14.67
F ⁻	0.00			0.00		0.02									
O ₂	0.02	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.02						
CH ₄	0.13	0.44	0.69	0.01	1.31	0.24	0.01	1.00	1.12	0.40	no sample	0.55	0.81	0.03	0.15
pH	6.8	7.3	6.8	7.1	6.9	7	6.6	6.5	6.7	7.9	7.3	6.9	6.9	7.1	7.4
Conductivity (mS/m)	82	520	356	53	129	1747	133	863	1460	81	470	340	118	192	147
Dry weight (mg/L)	590			290		17000									
Colour	sortbrun m. sand	sort	sort	farveløs m partikler	m silt	grålig m partikler	gråbrun	farveløs	Brun/sort	0	0	0	brun	brun	0
Temperature (°C)															
Comments		H2S lugt	H2S lugt	0	10.8	10.9	12.9	10.7	12.3	15.9	0	14.3	16.4	14.6	16.4
					0	0	H2S lugt	H2S lugt	sterk H2S lugt	0	slange stoppet	0	H2S lugt	0	H2S lugt
Sum cations (meq/L)	15.58	89.31	75.69	5.48	26.35	242.19	16.47	166.51	291.16	10.10	69.07	64.73	54.43	30.14	24.09
Sum anions (meq/L)	12.38	56.57	36.70	4.98	19.38	260.90	15.00	134.74	187.71	9.17	33.16	49.57	32.05	27.32	22.37
Diff cat-an (meq/L)	3.20	32.75	38.99	0.50	6.98	-18.71	1.47	31.76	103.45	0.93	35.91	15.16	22.38	2.82	1.72
Relativ diff (%)	11%	22%	35%	5%	15%	-4%	5%	11%	22%	5%	35%	13%	26%	5%	4%