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Ground water composition at
Bryggen in Bergen:
Temporal and spatial
variation, autumn 2011





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REPORT no
11031267

April 2012

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Case: 11031267

Date: 16th of April 2012

Title:

Ground water composition at Bryggen in Bergen: Temporal and spatial variation, autumn 2011

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Summary:

On request from Riksantikvaren in Norway, the chemical composition of 40 groundwater samples from dipwells and piezometers 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 and Matthiesen 2008; Matthiesen 2008b). New observations show how the groundwater underneath the drained area is influenced by processes in the unsaturated layers above, notably by an increased concentration of dissolved iron, manganese and sulphate. The origin of these species is discussed, but it is too early to evaluate the exact consequences for the preservation conditions. In the central area of Bryggen it is confirmed that there is a correlation between the depth and the composition of the water in the cultural layers, and the results and predictions from a simple geochemical modelling from 2009 has been confirmed (Matthiesen 2009). 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. Along the sheet piling an increased water flow has been confirmed and demonstrated even more clearly than during earlier sampling campaigns. At the quay front the results from a study in 2009 (Matthiesen 2010b) have been confirmed, i.e. there seems to be a frequent supply of seawater to the uppermost porous cultural layers, which may give a substantial decay of organic material by sulphate reduction. Seawater supply to the deeper dipwells is more limited, and at MB9 inside Fiskebutikken the salt and sulphate concentration has decreased significantly since 2009. The groundwater data from autumn 2011 are compared to results from earlier sampling campaigns in 2002-2009. In general there is only a modest temporal variation in the water composition. The exceptions are mainly found along the sheet piling and at the harbour front, where some of the dipwells show more dynamic conditions.

The data may be further evaluated in a combined hydrological-geochemical model. During the ongoing mitigation work monitoring should be supplemented by automated loggers and frequent sampling along the sheet piling and in the drained area. Next full sampling in all dipwells and analysis for all chemical species should take place in 3-5 year time.

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Appendix 1: Results from chemical analysis of groundwater from autumn 2011

Introduction

At Bryggen in Bergen an artificially lowered ground water level has locally led to decay of organic cultural deposits and settling of the buildings above (Jensen 2007). Work is currently on going to raise the water level and improve the preservation conditions.

Close to 40 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 represented the preservation conditions (Matthiesen 2006) and were published in a peer reviewed paper (Matthiesen 2008b). In April 2007 a partial sampling covering 9 dipwells was made, and the results were included in de Beer and Matthiesen (2008) In May 2008, sampling was made from 28 dipwells (Matthiesen 2008c) and the results were used for modelling the decay of organic material in the deposits, using the geochemical modelling tool PHREEQC (Matthiesen 2009). By 2011 the number of dipwells had increased to 39, and groundwater was sampled from all the wells during the autumn 2011. The National Museum of Denmark has been contracted by Statsbyg/Riksantikvaren to interpret the results in relation to the present preservation conditions in the saturated deposits beneath Bryggen, and – after repeated sampling in 2012 and 2013 – to evaluate if the planned raising of the groundwater level on Bryggen results in any changes of the groundwater chemistry and preservation condition.

Site and methods

An overview of the dipwells installed from 2001 to 2011 is presented in Figure 1.



Figure 1: Map of Bryggen, showing the position of the different dipwells. Dipwell numbers are best seen in the electronic version of the report. Graphics: Hans de Beer.

The dipwells 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 over one to several meters at the lower end 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.

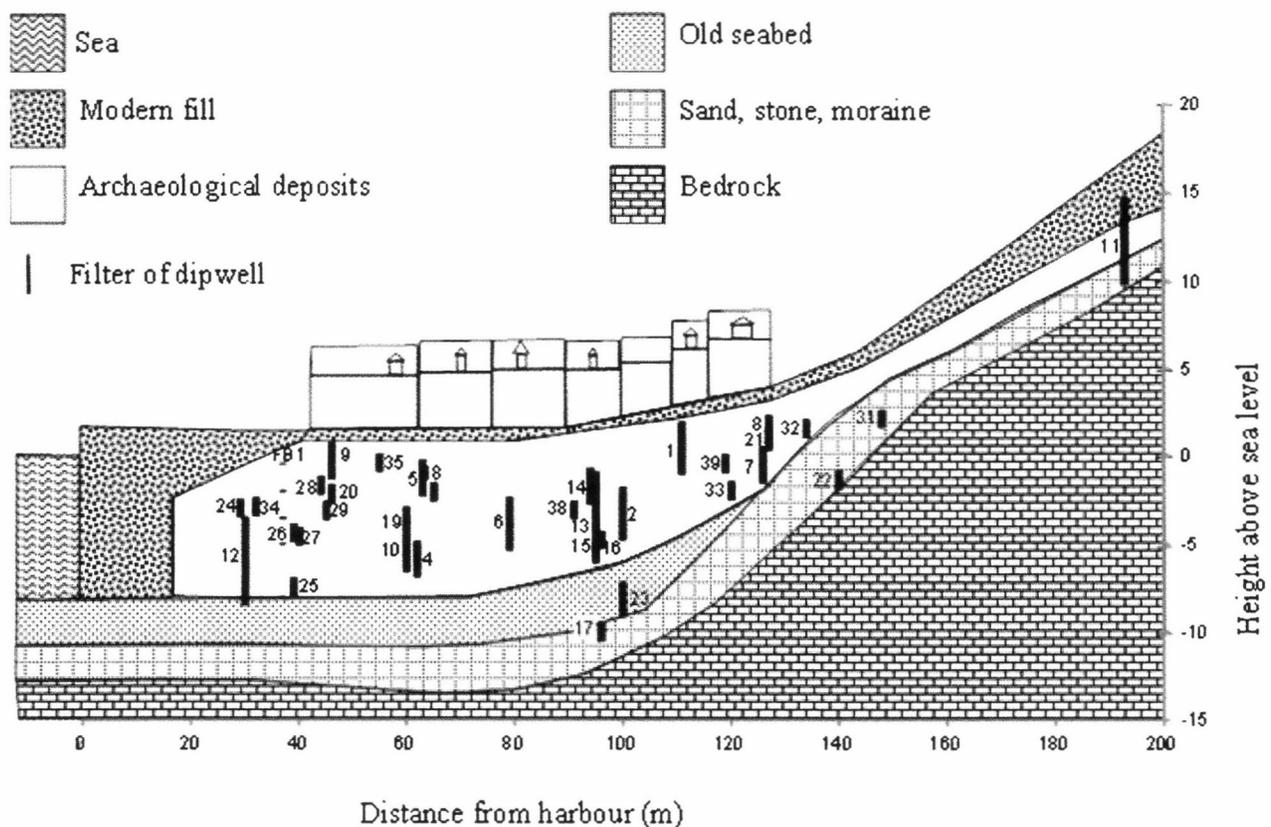


Figure 2: Profile perpendicular to the quay front showing the filters from the different dipwells on Bryggen. The depth and extent of the different soil strata is only sketched – in reality the depth to the natural deposits varies considerably across the area.

Water has been sampled from the dipwells on several occasions from 2002 to 2011. All sampling has been carried out by Multiconsult AS and NOTEBY, except for a partial sampling in April 2007, which was made by Hans de Beer, NGU. The sampling procedure is described in NS9451 (2009) and references therein, but some details and changes are described below.

All dipwells are emptied (purged) before sampling takes place, to ensure that “fresh” water from the cultural deposits is sampled. Some of the wells only refill very slowly and for these purging takes place the day before the actual sampling. Some of the chemical species in the water require special sampling and conservation, so several sample bottles are filled at each dipwell according to the instructions from the laboratory. Samples for metal ions should be filtered in the field before conservation according to NS9451 (2009), but due to a misunderstanding this filtering was not done in 2011. Special attention is given to the samples for methane measurements, as this gaseous analyte can easily escape when the pressure is lowered, but still it cannot be excluded that some methane was lost during sampling in 2011. pH, conductivity, oxygen content and temperature should ideally be measured in-line during the sampling using a flow-through cell with sensors for these parameters, but this was not done in 2011, as no flow-through cell was available. Instead pH was measured in the laboratory, and two weeks after the sampling it was attempted to measure conductivity and oxygen directly in the dipwells with dipping probes lowered into the wells. The measurements directly in the dipwells didn’t work out for conductivity, and for oxygen the method may give erroneous results due to oxygen carried down into the dipwell by the probe itself (thus all

results below 1.5 mg/L has been discarded as it is estimated that they may be due to pollution). Sampling took place from 28th of August to the 9th of September 2011. Four water samples were lost during transport, so new samples were taken from dipwell 18, 22, 31 and 39 in October 2011. Dipwell MB38 was installed later and ground water was sampled on the 22nd of December. The samples were sent to the laboratory for a detailed groundwater analysis, covering pH, alkalinity/bicarbonate, salt (sodium, chloride), nutrients (ammonium, nitrate, phosphate), redox active species (sulphate, nitrate, dissolved iron, dissolved manganese, sulphide, methane), and other major ions (calcium, magnesium, potassium). During the later years Eurofins in Denmark has made all ground water analyses, as they offer this standard package with a good analytical quality and at a reasonable price.

Results

All results from the laboratory are listed in Tables in Appendix 1, along with dipwell characteristics and the groundwater level measured during the sampling. The full laboratory reports are available on request as .pdf files. The results for the different species are shown as bar charts in Figures 3-8, showing both the results from Autumn 2011 (upper chart) and time series for the dipwells where there are multiyear data (lower two charts). Results from the first sampling rounds in 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.

In Figures 9-12 the results are shown as piecharts for the major ions (Figure 9 and 11) and redox active species (Figure 10 and 12) emphasizing the spatial distribution of the dipwells. Figure 9 and 10 show the results projected onto a vertical profile from the harbour front and inland, where the different soil strata beneath Bryggen are sketched. Figures 11 and 12 show the horizontal distribution compared to a map of Bryggen, and where the data from 2008 are included for comparison.

No data are given for MB30 as the dipwell was empty at the time of sampling, and no data are given for the piezometer FB1, 7.5 m as the tube was clogged. MB3 was removed some years ago and dipwells MB36 and 37 have been installed after the sampling campaign. Other gaps in the data series are due to the concentrations being below the detection limit of the method (in which case they are set to “zero”), or because the parameters were not analysed in some of the sampling campaigns (which is then mentioned in the legend).

Salt:

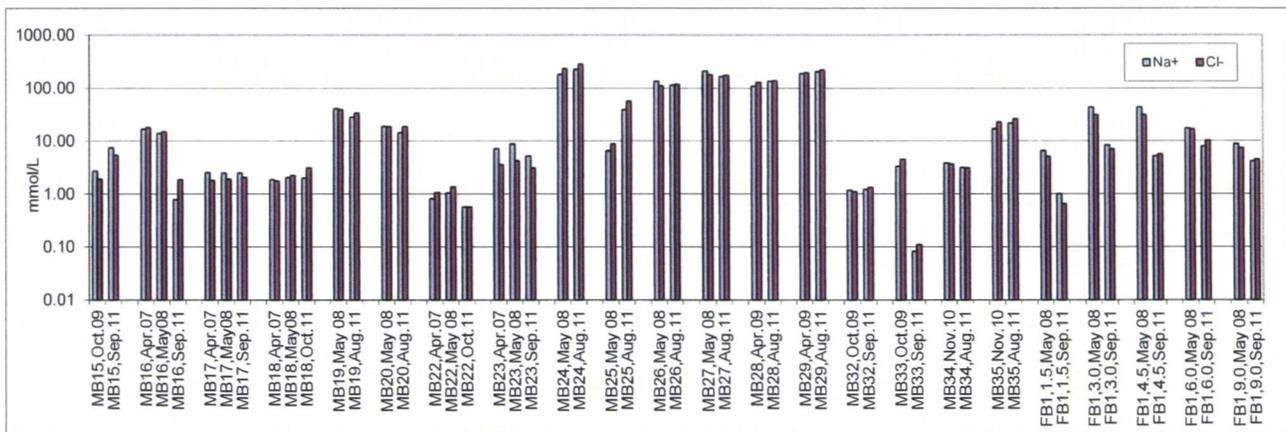
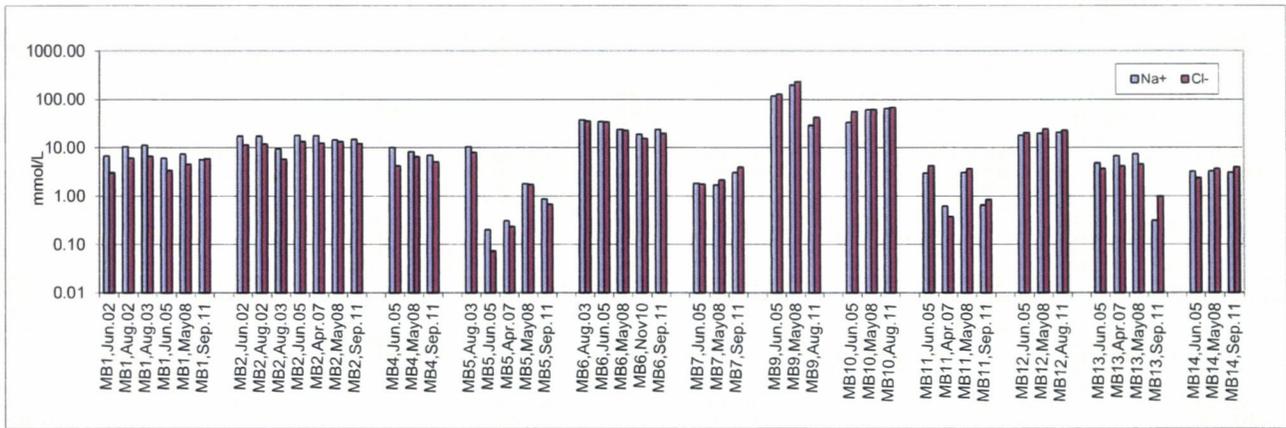
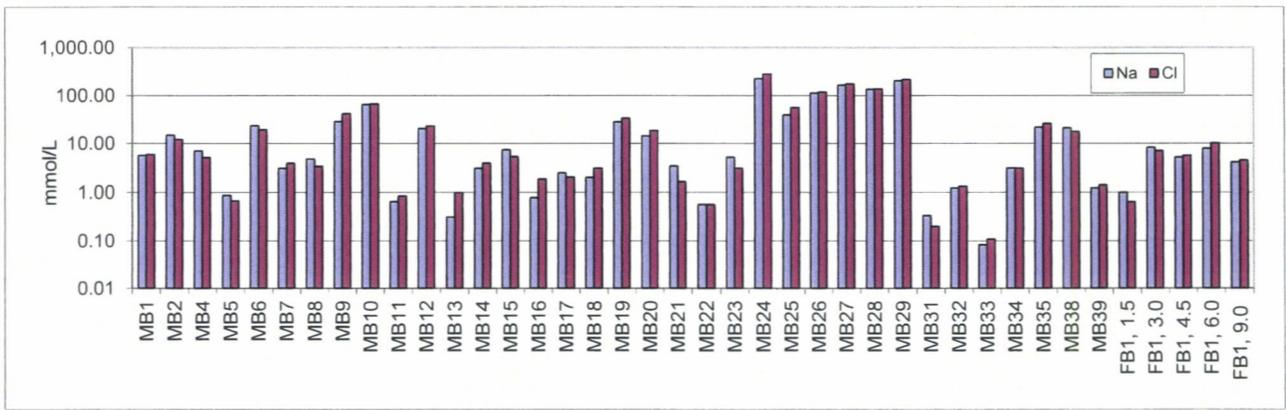


Figure 3: Concentrations of sodium (Na) and chloride (Cl) in the dipwells in Autumn 2011 (upper diagram) and as time series (lower 2 diagrams). Note logarithmic scale. For results in mg/L the numbers in mmol/L must be multiplied by 22.99 for Na, and 35.45 for Cl.

Nutrients:

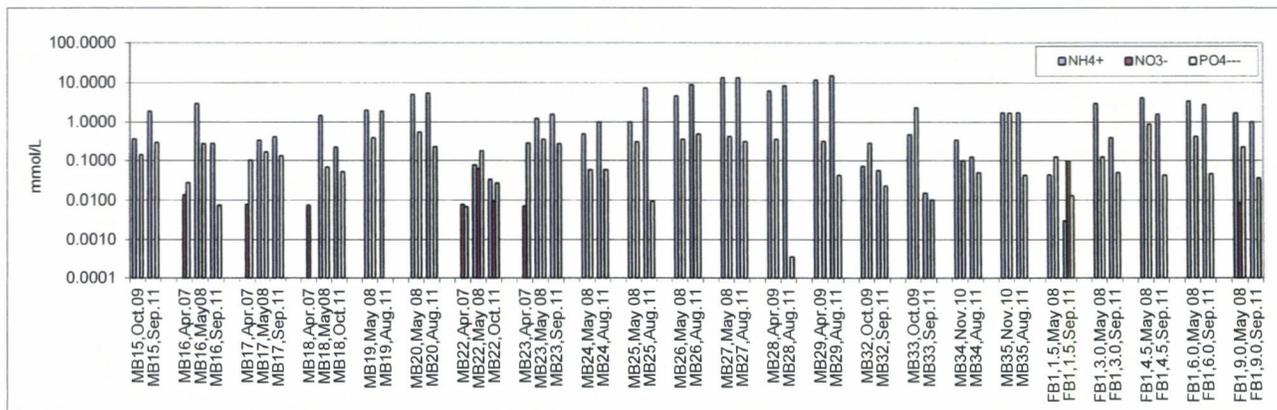
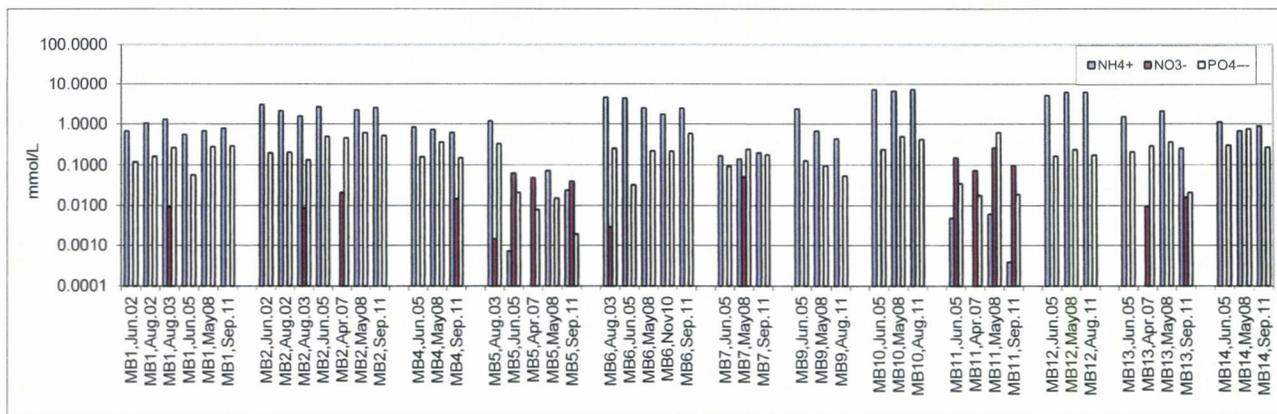
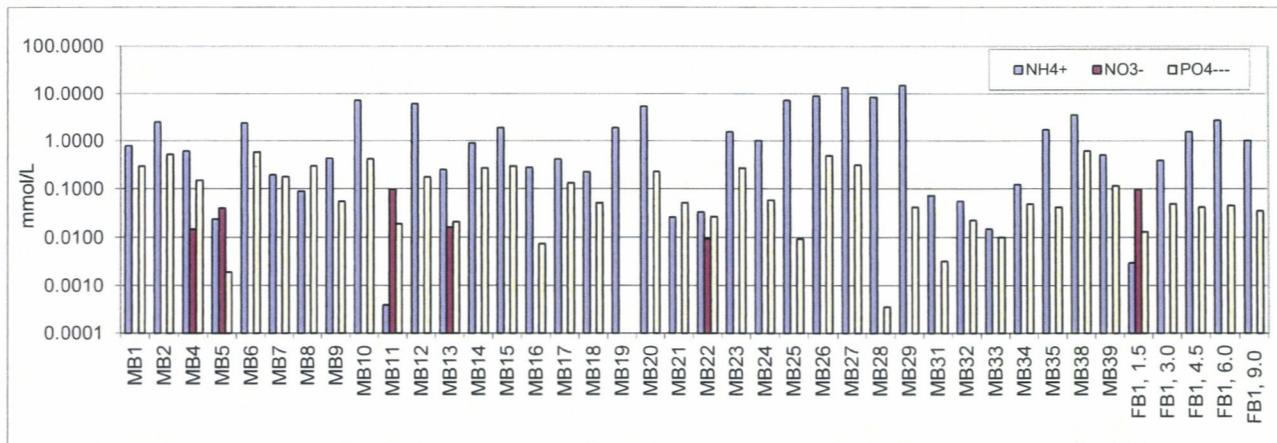


Figure 4: Concentrations of ammonium (NH_4^+), nitrate (NO_3^-) and phosphate (PO_4^{3-}) in the dipwells in Autumn 2011 (upper diagram) and as time series (lower 2 diagrams). Note logarithmic scale. Ammonium wasn't analysed in Apr. '07. For results in mg/L the numbers in mmol/L must be multiplied by 14.01 for nitrate and ammonium (to give mg N/L) and by 94.97 for phosphate (to give mg PO_4^{3-} /L).

Oxidants:

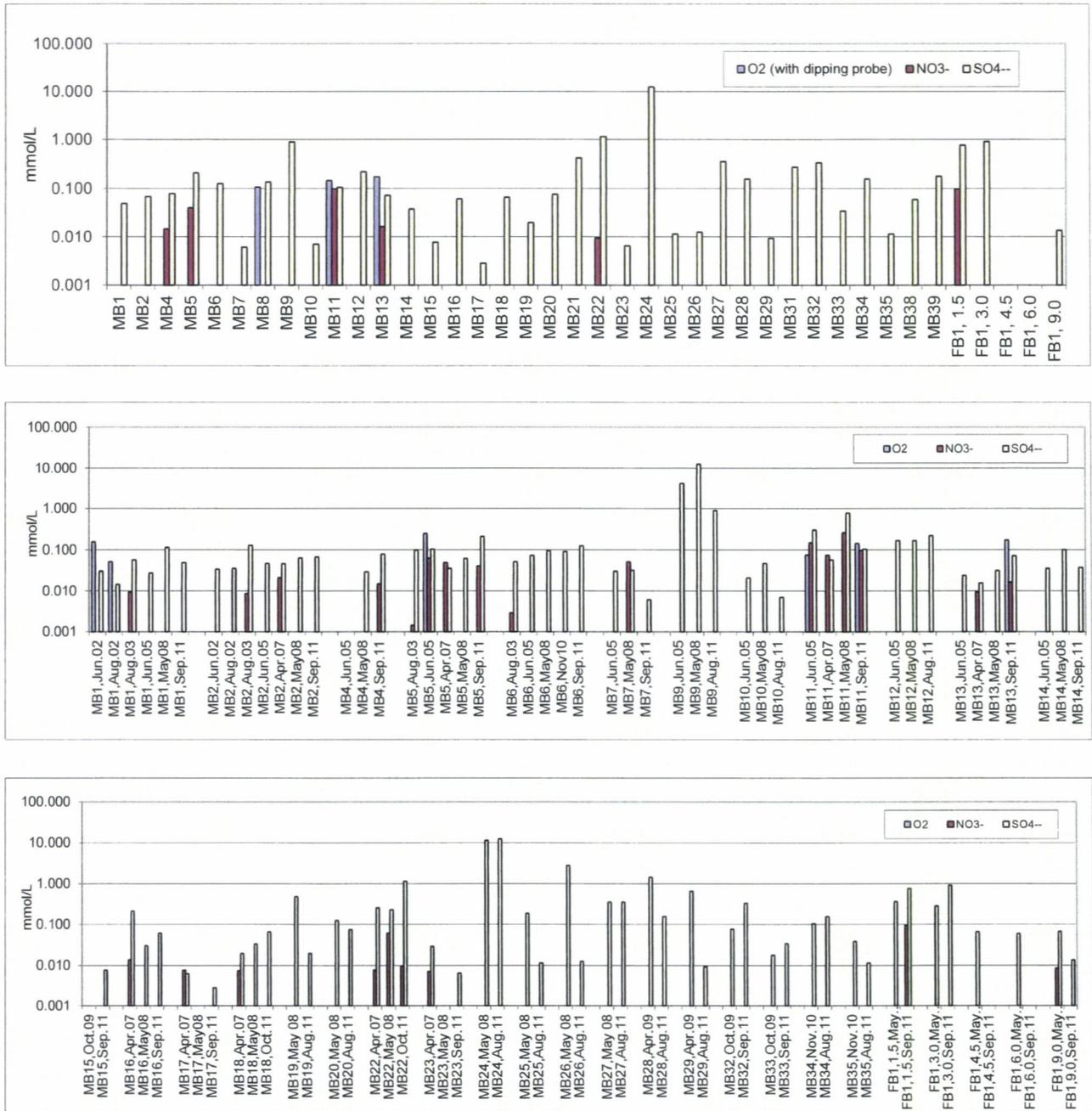


Figure 5: Concentrations of different oxidants in the dipwells in Autumn 2011 (upper diagram) and as time series (lower 2 diagrams). Note logarithmic scale. Due to pollution problems oxygen measurements below 0.05 mmol/L have been discarded from the results and oxygen wasn't analysed at all in May '07. 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:

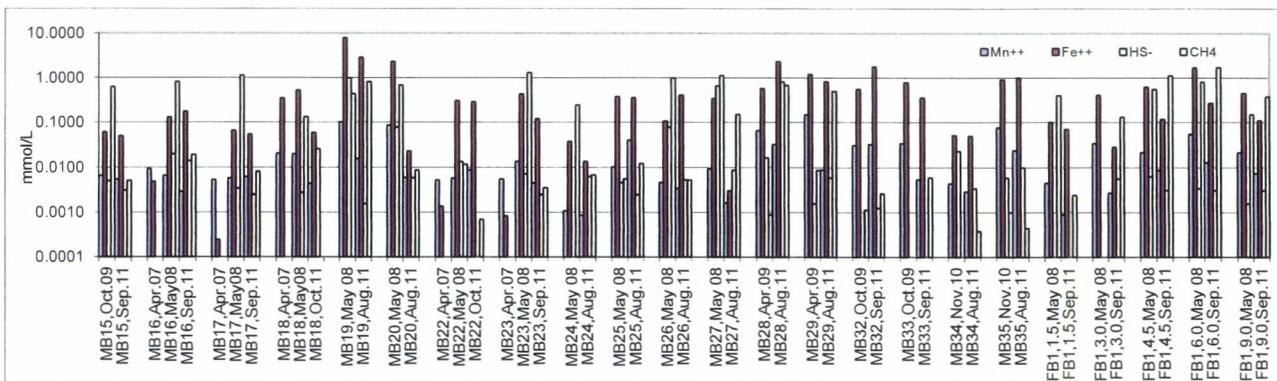
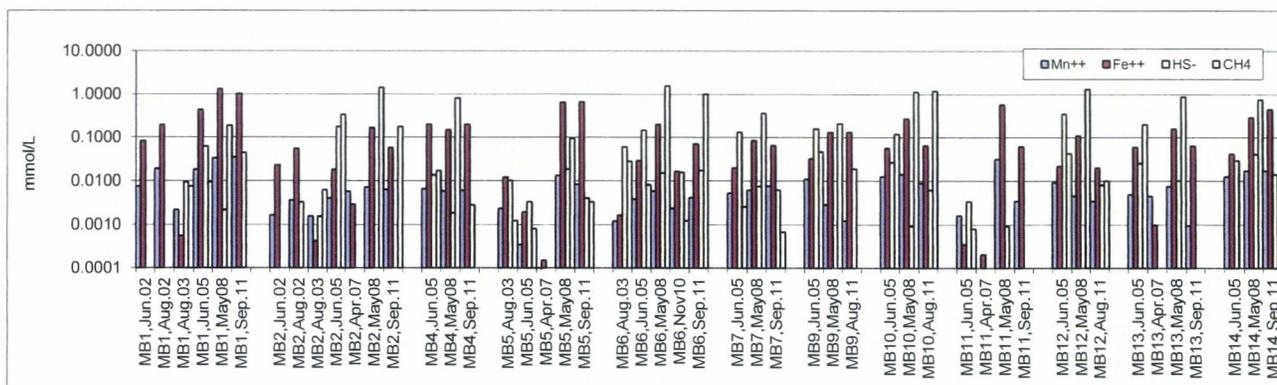
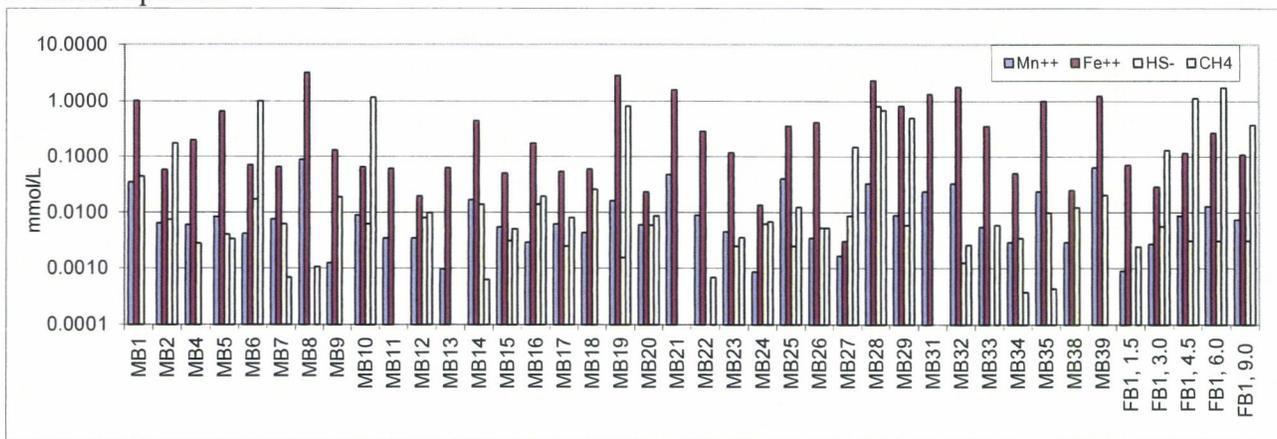


Figure 6: Concentrations of different reduced species in the dipwells in Autumn 2011 (upper diagram) and as time series (lower 2 diagrams) – NH_4^+ is shown in Figure 4. Note logarithmic scale. For results in mg/L the numbers in mmol/L must be multiplied by 54.94 for manganese, 55.85 for iron, 32.06 for sulphide (to give mg S/L), and by 16.04 for methane (to give mg CH_4 /L). Sulphide wasn't analysed in 2002 or 2007, and in May '08 the results for MB2, MB9, MB12 and MB24 were reported as "too high" for the analytical method applied. Methane was not measured in 2002, and in 2003, 2005 and possibly 2011 some methane may have been lost during the sampling resulting in too low values.

pH and bicarbonate:

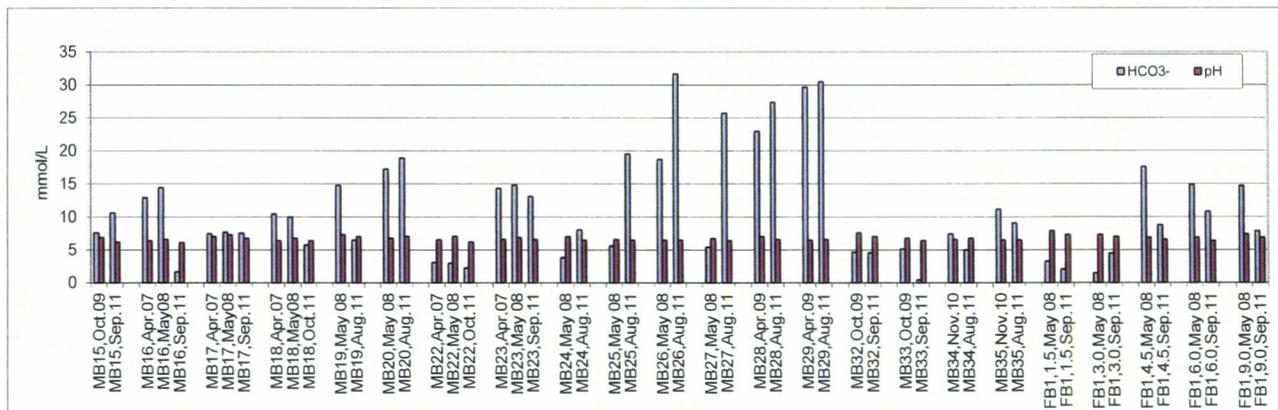
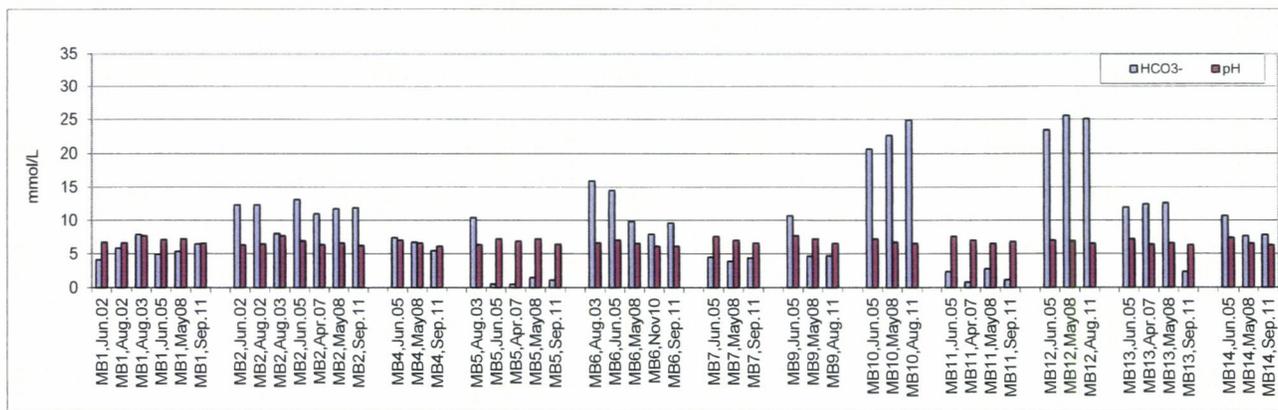
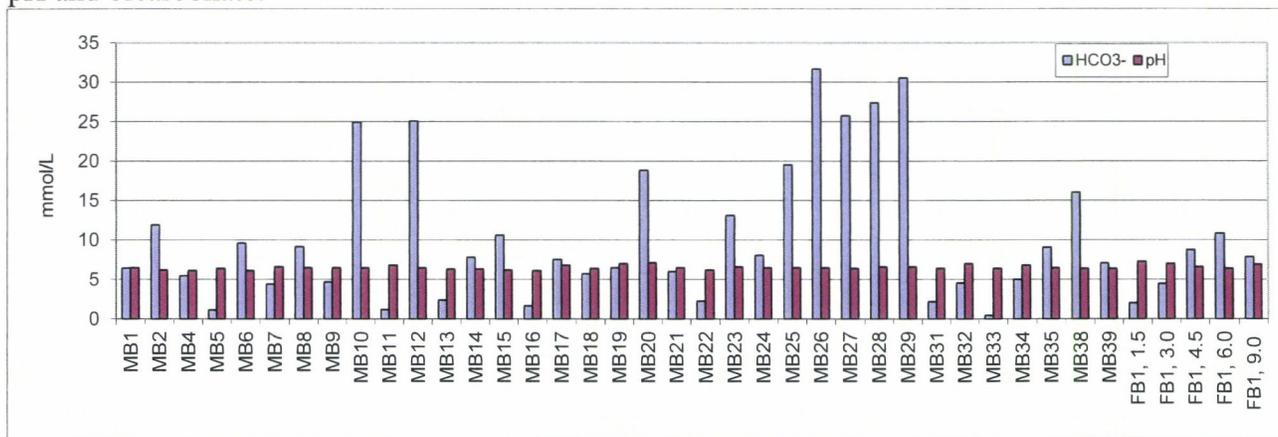


Figure 7: pH and bicarbonate in the dipwells in May 2008 (upper diagram) and as time series (lower 2 diagrams). pH is unitless, while the bicarbonate (HCO₃⁻) has the unit mmol/L.

Other major ions:

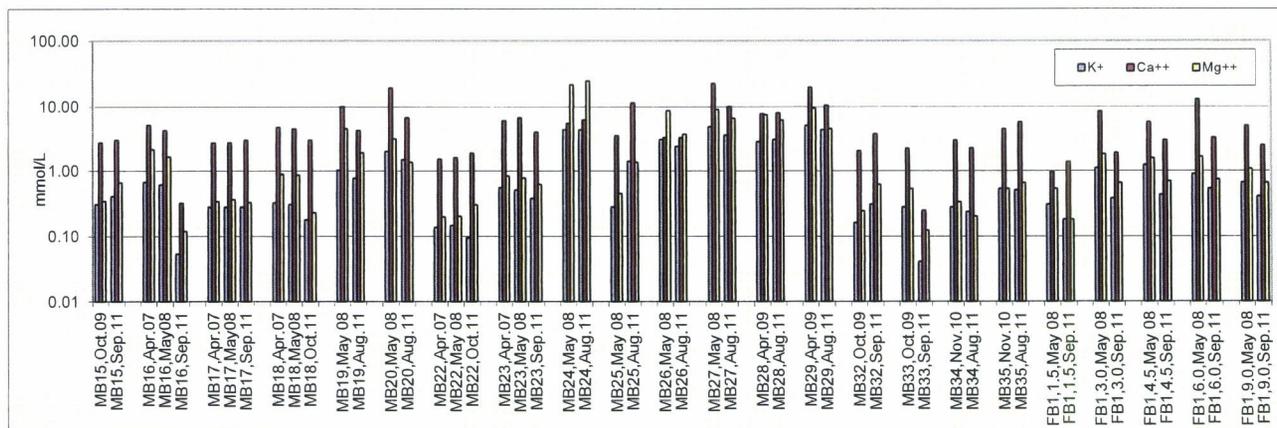
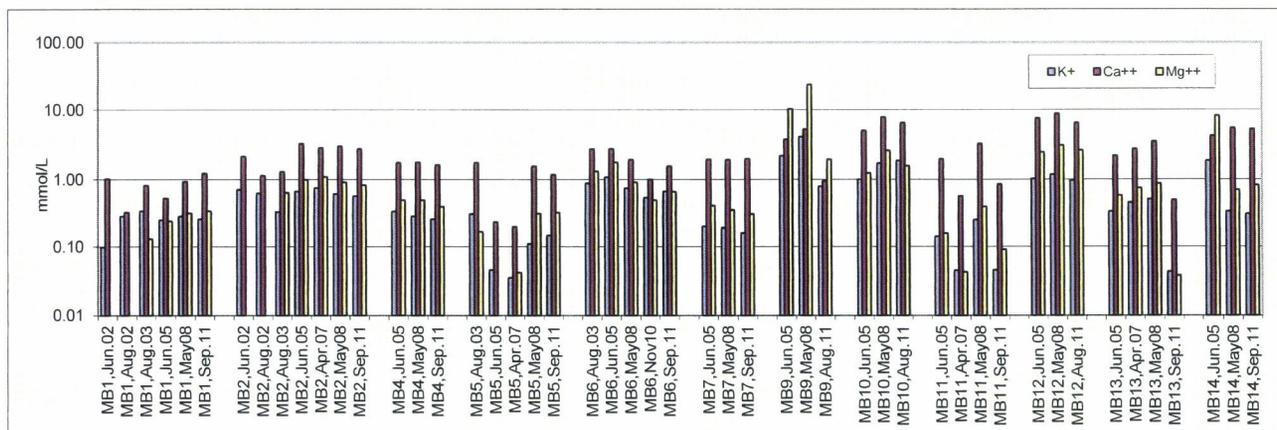
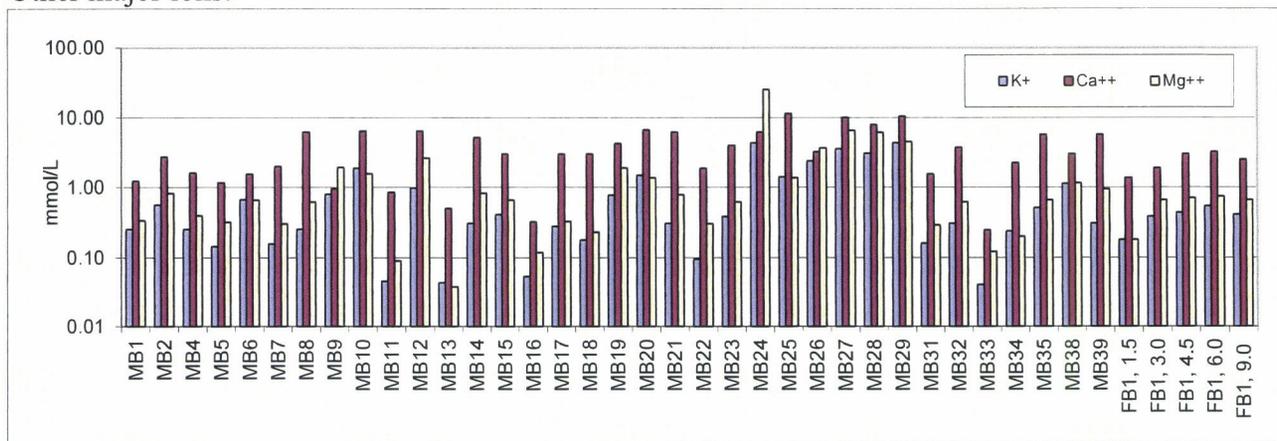


Figure 8. Concentrations of potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) in the dipwells in Autumn 2011 (upper diagram) and as time series (lower 2 diagrams). Note logarithmic scale. For results in mg/L the numbers in mmol/L must be multiplied by 39.10 for potassium, 40.08 for calcium, and by 24.31 for magnesium. Magnesium wasn't analysed in 2002, and the result for MB14 in 2005 is possibly erroneous.

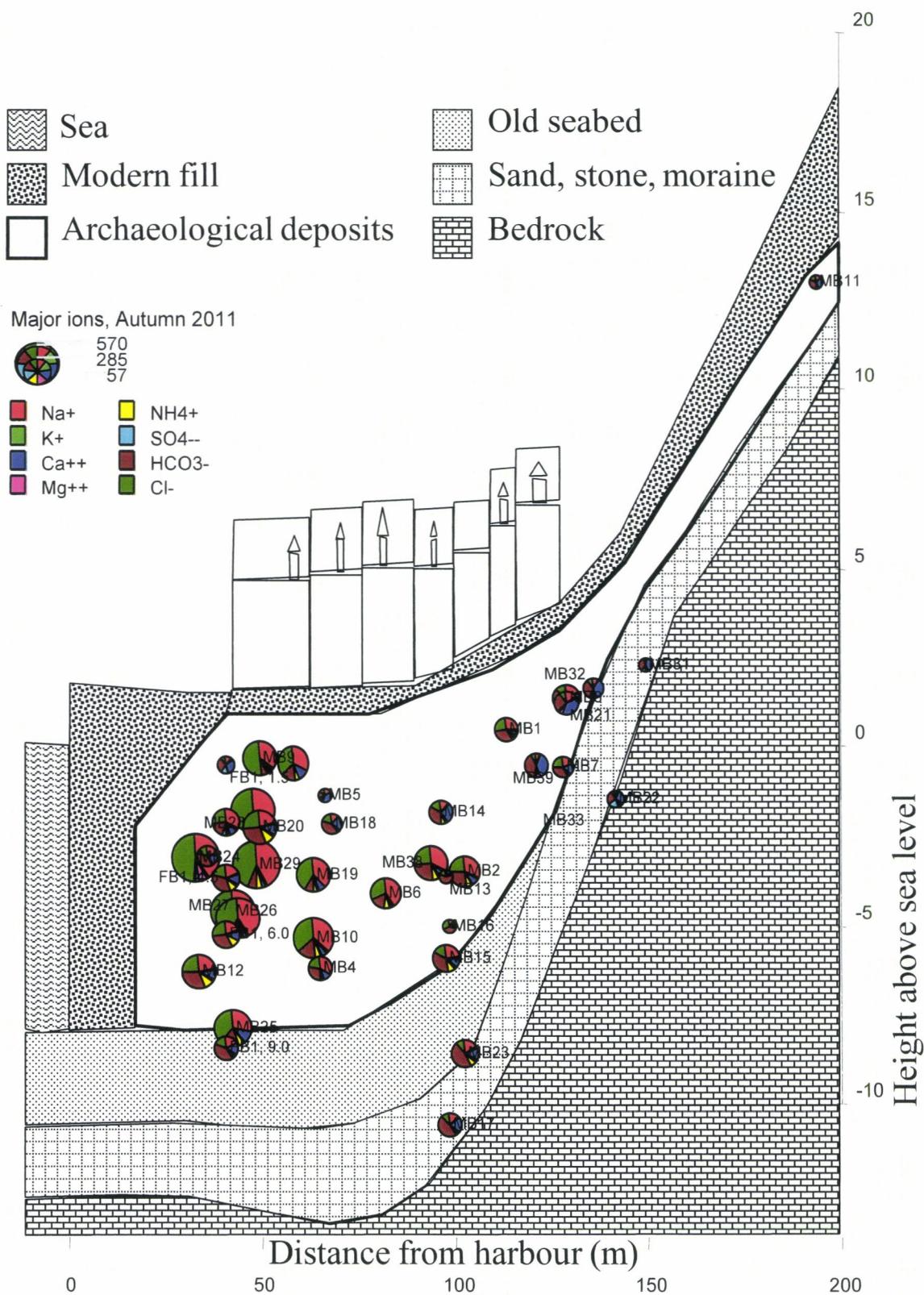


Figure 9: Transect through the deposits showing major ions in water samples from the Autumn 2011. Unit is mmol/L (not meq/L). The diameter of the circle represents the total amount of ions on a logarithmic scale; the concentrations in MB33 are too low to be seen. The depth and extent of the different soil strata is only sketched – in reality the depth to the natural deposits varies considerably across the area.

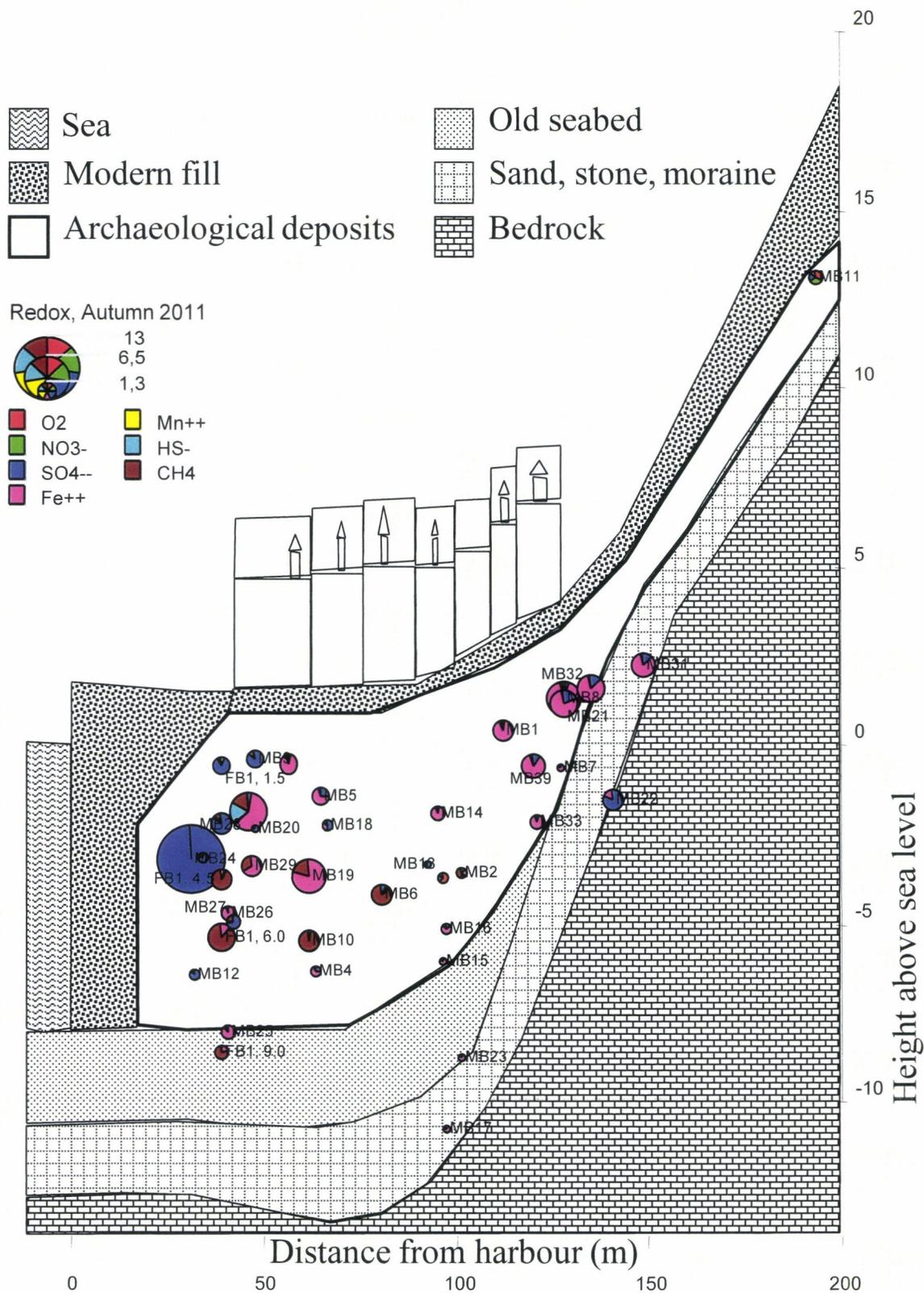


Figure 10: Redox sensitive species in water samples, Autumn 2011. Unit is mmol/L (not meq/L). The area of the circle represents the total amount of redox sensitive species. The depth and extent of the different soil strata is only sketched – in reality the depth to the natural deposits varies considerably across the area.

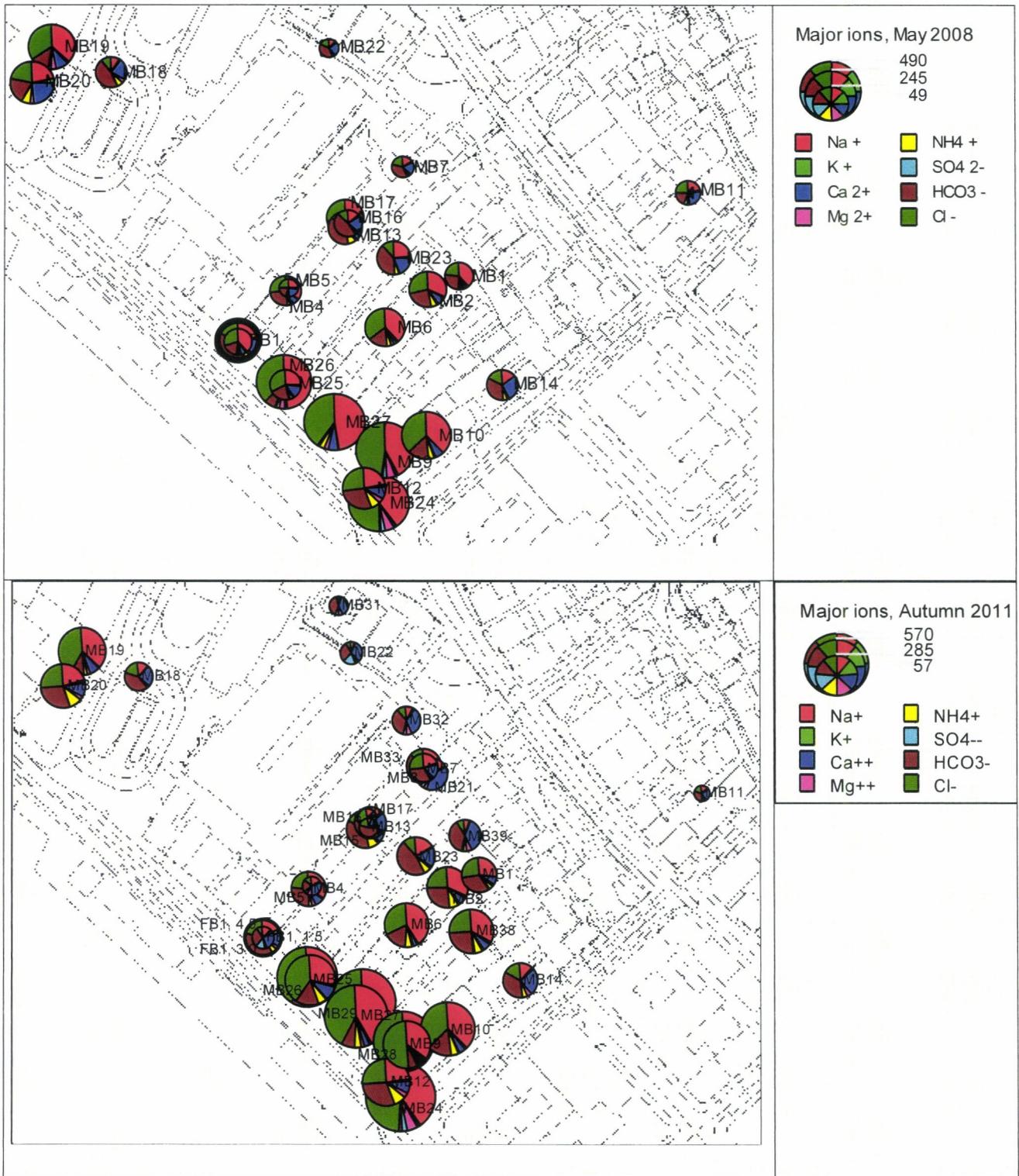
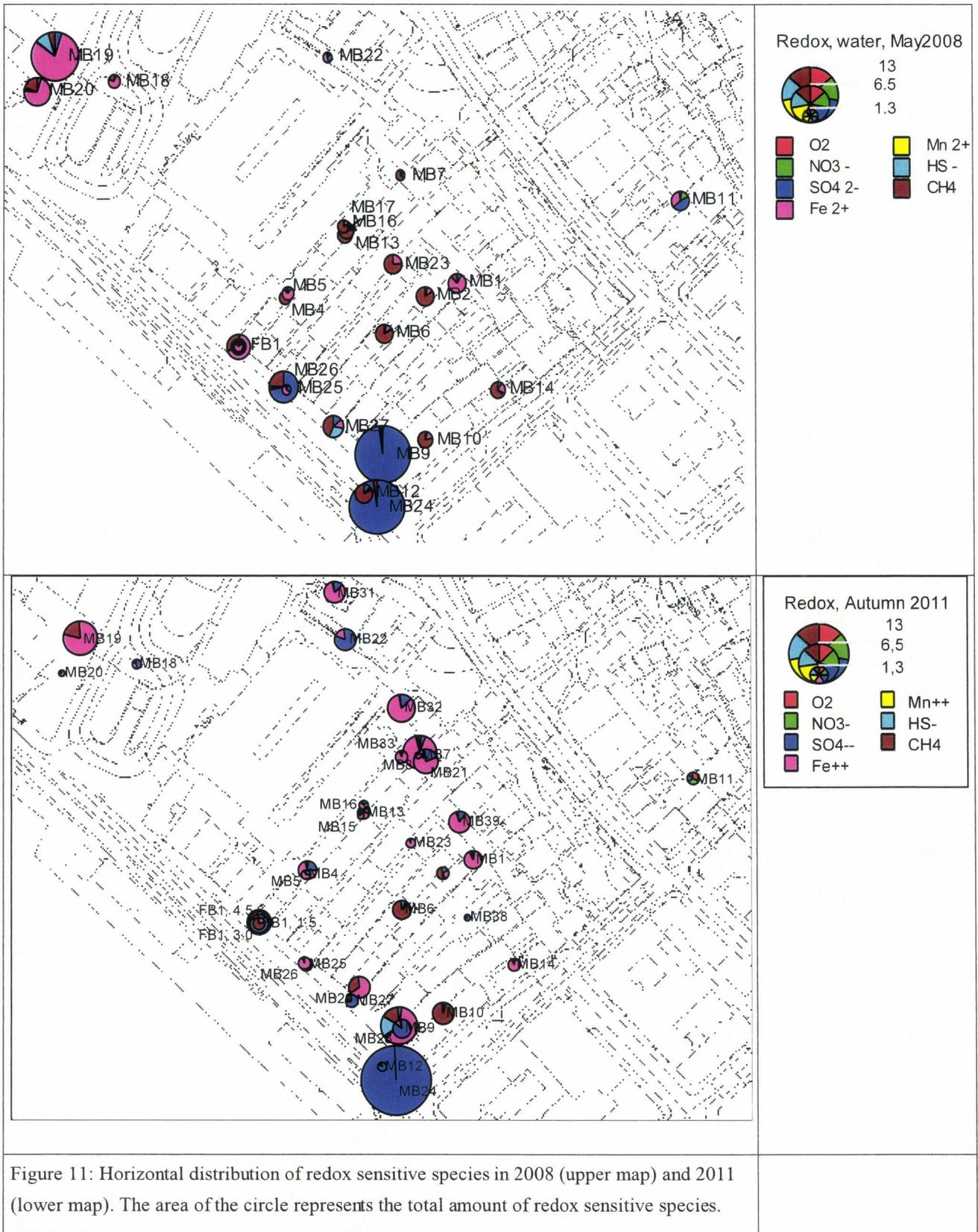


Figure 11: Horizontal distribution of major ions in 2008 (upper map) and in 2011 (lower map). The diameter of the circle represents the total amount of ions on a logarithmic scale; the concentrations in MB33 are too low to be seen.



Discussion

The ground water sampling is a cornerstone in the monitoring programme at Bryggen. After the first major sampling campaign in 2005 a conceptual model of the ground water formation and – chemistry was established, and it was demonstrated how the groundwater chemistry reflects the preservation conditions (Matthiesen 2006; Matthiesen 2008b). The picture was refined by a partial sampling in 2007 (de Beer and Matthiesen 2008) and not at least by the last major sampling campaign in 2008 where special focus on the sampling procedure for methane gave the first reliable results for this gaseous (and very volatile) compound (Matthiesen 2008c). Based on the results from 2008 a preliminary numerical model was made in the geochemical modelling tool PHREEQC (Matthiesen 2009) which gave a quantitative estimate of the actual decay rate in the most stagnant, waterlogged deposits. The new data from 2011 makes it possible to validate this numerical model and furthermore the increased number of dipwells at Bryggen makes it possible to evaluate whether our understanding of the groundwater formation and -chemistry in the area is still valid or needs to be modified.

The first ground water samples were taken at Bryggen in 2002, and with the new sampling in 2011 there are now time series covering 10 years for some of the dipwells. This makes it possible to see whether the ground conditions are stable or changing over time, and give an excellent baseline for comparison with future ground water samples in order to identify possible changes after the ground water level has been raised on Bryggen. A comparison of groundwater data over decades requires a continued focus on the analytical quality of the results, to ensure that they are actually representative and comparable.

Analytical quality

For many of the dipwells the laboratory notes in their report that the samples used for metal analysis (Fe^{2+} , Mn^{2+} , Ca^{2+} , K^+ , Mg^{2+} , and Na^+) contained solid particles (Appendix 1). This is due to the fact that the samples were not filtered in the field in 2011. Nitric acid is added to the metal samples in the field, which may release different ions (as for instance Fe^{2+} and Ca^{2+}) from the solid particles and thereby give too high results for dissolved metal ions. Furthermore the laboratory noted, that some of the bottles containing samples for sulphide analysis were not completely filled, in contradiction to the sampling instructions. This may result in escape of sulphide and measurement of too low sulphide concentrations.

Apart from these notes from the laboratory, 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 (Appendix 1). The concentrations of the different ions may be used to calculate a theoretical dry residue and compare this with the measured dry weight; however this comparison is not very good if there is precipitate in the samples.

Alternatively it is possible to calculate a theoretical conductivity to compare with measured values, but this parameter was only measured in a few dipwells 2 weeks after the ground water sampling in 2011. Furthermore, there are some chemical rules that allow us to check if for instance the results from the different redox active species contradict each other. Finally, it is possible to compare with the results from previous years and evaluate if the observed changes are likely or if they may be due to analytical bias.

These tests have been made for all the dipwells, and generally show that most results from 2011 are consistent, giving good confidence in the data. However, there are also some exceptions where there is some doubt about the quality of the results:

- There is a large electrical imbalance for dipwells MB5, 8, 9, 13, 14, 16, 19, 21, 31, 32, 33, and 39.

Most of these samples (except MB 9, 14, 19, and 39) stem from dipwells near the sheet piling or from the drained area. It hasn't been proved yet what is the cause of the imbalance, but it can for instance occur if ions are released from solid particles in the samples before analysis, if samples with high concentrations of dissolved iron are oxidised or if calcium carbonate (or other solids) precipitate before the analysis takes place. This point is discussed in more detail below.

- The oxygen measurements in 2011 were made with a dipping probe directly in the dipwells 2 weeks after the sampling took place. This method gives a high risk of pollution and values beneath 0.05 mmol/L have been discarded.

- The methane results in 2011 are significantly lower than in 2008 for most dipwells. Methane (CH₄) is difficult to sample because it escapes very easily as a gas, and in 2008 special attention was given to the procedure, using an in line sampling method where water at in situ pressure was sampled directly into evacuated bottles. The sampling in 2011 seems to have been less successful and the results should be interpreted with some caution.

- 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).

These comments should be taken into consideration when analysing the data further and comparing them with earlier results. Still, the overall picture is that the analytical quality is acceptable and that the data are valid for comparison.

Spatial variation

Based on results from the monitoring, the Bryggen area has been divided into sub-areas with different preservation conditions (Figure 12a). A conceptual model of the groundwater formation

and -chemistry in these areas has been introduced and discussed in previous papers (de Beer and Matthiesen 2008; Matthiesen 2008b; Matthiesen 2008c) - Figure 12b.

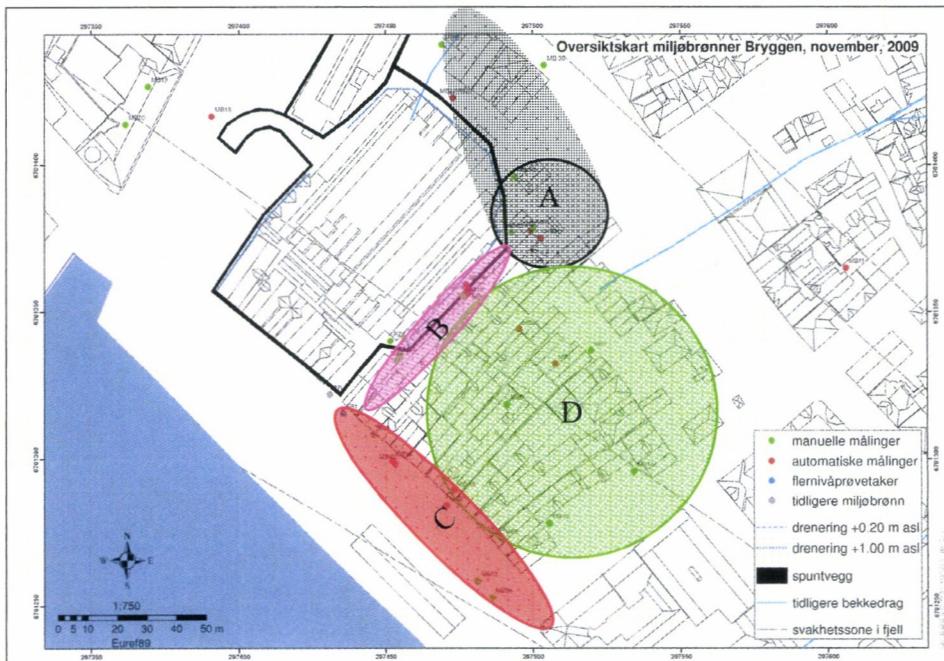


Figure 12a: Areas of Bryggen characterised by different preservation conditions.

- A: Drained area
- B: Rainwater influenced along sheet piling
- C: Seawater influenced
- D: Stagnant conditions
- E: Water from bedrock/natural deposits

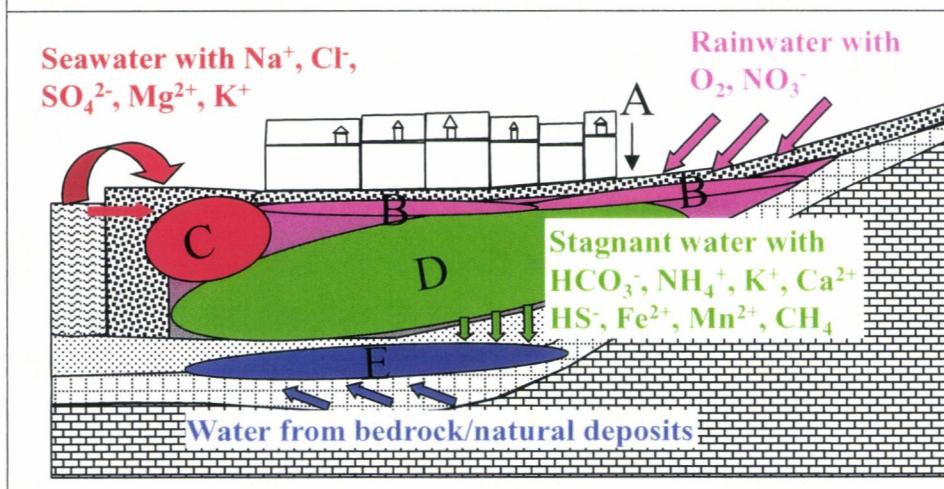


Figure 12b: Conceptual model of the groundwater formation in the different areas on Bryggen

Since 2008 two studies have been made involving ground water sampling from new or selected dipwells: at the harbour front (Matthiesen 2010b) and in the area bordering the sheet piling (Matthiesen 2010a). The study at the harbour front focused on the effect of flooding and sulphate reduction. It showed that there is plenty of sulphate available in the upper soil strata in front of the buildings to sustain a high sulphate reduction rate and decay of organic material, as sulphate containing seawater is frequently supplied to these porous soil layers. The soil strata deeper than -4 m asl and beneath the buildings were more compact and sulphate supply was limited to slow diffusion processes, thereby also limiting the sulphate reduction. Flooding of the quay front area has become less frequent since 2007, where counter valves were installed in the sewer system. The study at the sheet piling indicated that both the horizontal and the vertical water flow is significantly faster near the sheet piling compared to the central parts of Bryggen. This corresponds

to a situation where “stagnant water” (green area in Figure 12) is more diluted or completely replaced by rain water (pink area in Figure 12).

With the ground water sampling in 2011 new dipwells have been added to the system, and it is interesting how these (as well as the older dipwells) fit into the model used until now. In Figure 13 the concentrations of different species are shown versus depth of the dipwell, and each dipwell is given a coloured symbol referring to the areas in Figure 12

The graphs in Figure 13, along with the piecharts in Figure 9-12 may be used to give a brief characterisation of the groundwater composition in each dipwell and area:

The seawater influence is dominant in MB9, MB24, MB26, MB27, MB28, MB29, all placed in the upper soil layers at the harbour front. The water in the dipwells is characterised by a high salt content, including the ions Na^+ , Cl^- , Mg^{2+} , K^+ and SO_4^{2-} that are all present in high concentrations in seawater. For some of the dipwells the concentrations vary substantially over time due to different influx of seawater, and furthermore the concentrations of sulphate may change due to sulphate reduction. These dipwells, and the possible effect of sulphate reduction at the quay front, are discussed in detail in Matthiesen (2008a) and Matthiesen (2010b). At the sampling in 2011 the seawater influence is surprisingly low in MB9, whereas MB25 and MB10 both have high salt contents indicating some seawater influence. The multi-level piezometer FB1 has been removed from the seawater influenced group, due to a low salt content in all sampling rounds.

The rainwater influence is most clearly seen in MB5 and MB11 both showing very dynamic conditions, but also other dipwells along the sheet piling such as MB4, MB13, MB15, MB16, MB33, FB1 1.5 and FB1 3.0 (and to some extent also MB7 and MB22) show signs of an increased “dilution” by rainwater. The rainwater contains small amounts of dissolved oxygen and NO_3^- (Figure 5), which may oxidise organic material in the soil, so the preservation conditions in the area are not ideal. The more precise consequences are estimated in Matthiesen (2010a). Some of the dipwells are characterized by a large error in the charge balance of the samples (Figure 13, lower right).

The groundwater in the **drained area** has not earlier been discussed on its own, but it includes dipwells MB21, MB22, MB30 (empty), MB31, MB32, and to some extent also MB7, MB8, MB21 and MB33, which may be placed in this group or in the rainwater influenced group (pink) due to their proximity to the sheet piling. The results from this group are characterised by high concentrations of dissolved Fe^{2+} , Mn^{2+} and SO_4^{2-} and a possible explanation of this signature is given below. It is remarkable that quite a few of the dipwells in this group are also characterized by a large error in the ion balance (Figure 13). High Fe^{2+} concentrations are also found in MB39 (in the outskirts of the drained area), MB19 (beneath a building in Slotsgaten) and MB28 (at the harbor front) but they do not necessarily all belong to the same group.

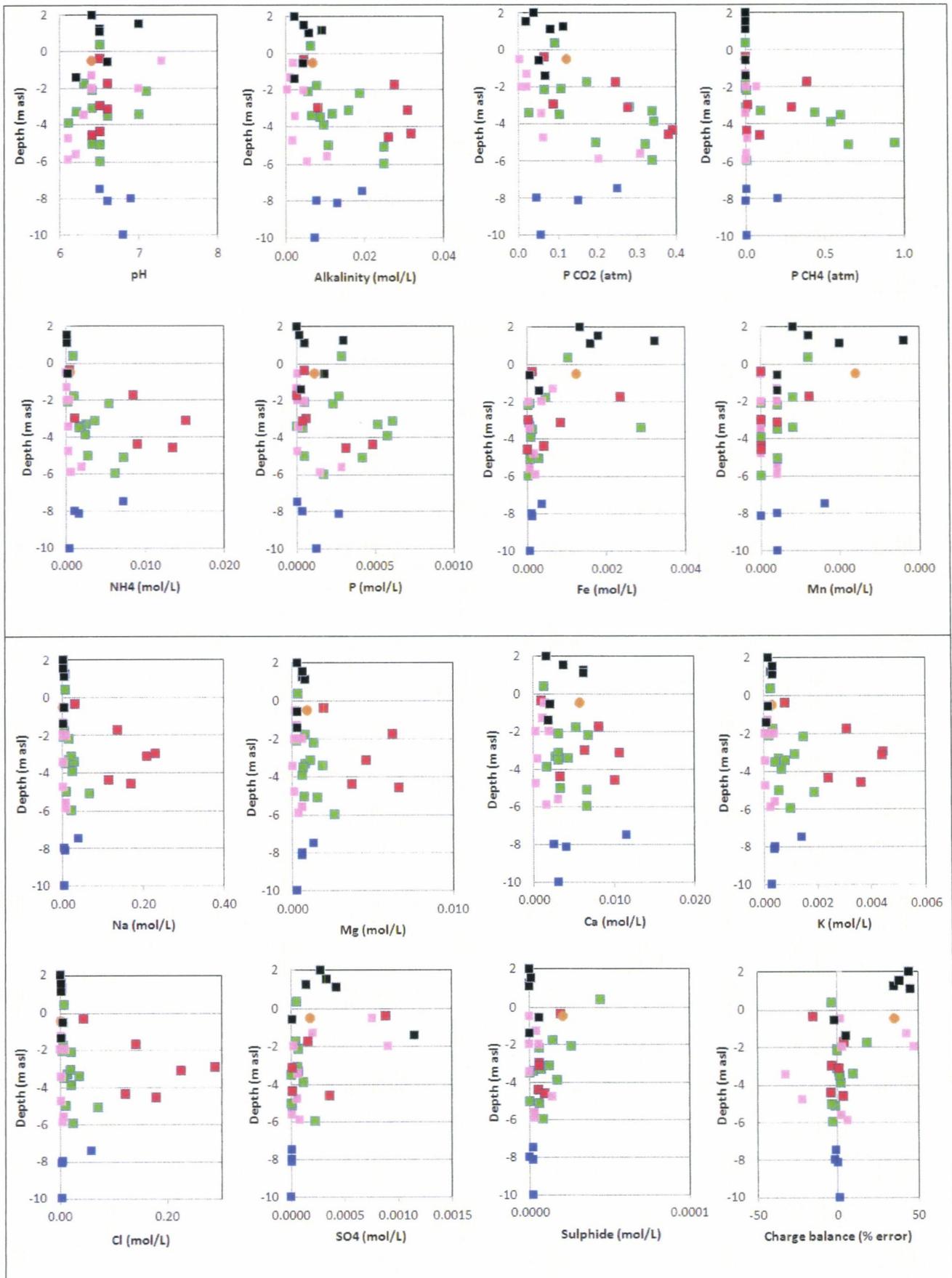


Figure 13: Results from groundwater analyses, where dipwells from different areas are shown with different colours, as described in the text. One of the newest dipwells, MB39, is marked orange. For MB24 the results for Mg and SO₄ are too high to be shown.

The **stagnant water** is found in its “purest” form in MB2 and MB6, but also MB1, MB10, MB12, MB14, MB18, MB19, MB20, MB38 and FB1 (4.5, 6.0 and 7.5) are considered belonging to this group. The water in the dipwells is dominated by Ca^{2+} , HCO_3^- , NH_4^+ , CH_4 as well as other reduced species, and generally the concentrations increases for the deeper dipwells. The preservation conditions in the deeper deposits are considered excellent in this region, and a (very low) decay rate has been estimated in Matthiesen (2009) based on groundwater data from 2008 from this group of dipwells.

Finally, the “**natural deposits**” are reached in MB17, MB23, MB25 and FB1 (9.0), and also in the higher lying dipwells MB22 and MB31 (included under the drained area). The chemical “signature” found in these dipwells is quite similar to what is found in dipwells above, only is it more diluted. This may be explained by a downwards flow of the groundwater from the organic-rich 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.

Conditions beneath the drained area (A)

The monitoring in the drained area A has up to now focused on the upper, unsaturated soil layers, where the conditions have been described as lousy (PresCon 1), and less on the waterlogged layers underneath. However, as the black points in Figure 12 indicates, the water samples from this area are characterised by relatively high concentrations of dissolved Fe^{2+} , Mn^{2+} and SO_4^{2-} . The distribution of Fe^{2+} may be seen in Figures 9 and 11 (the pink pie in the pie charts) and more detailed maps of the sulphate distribution are shown in Figure 14:

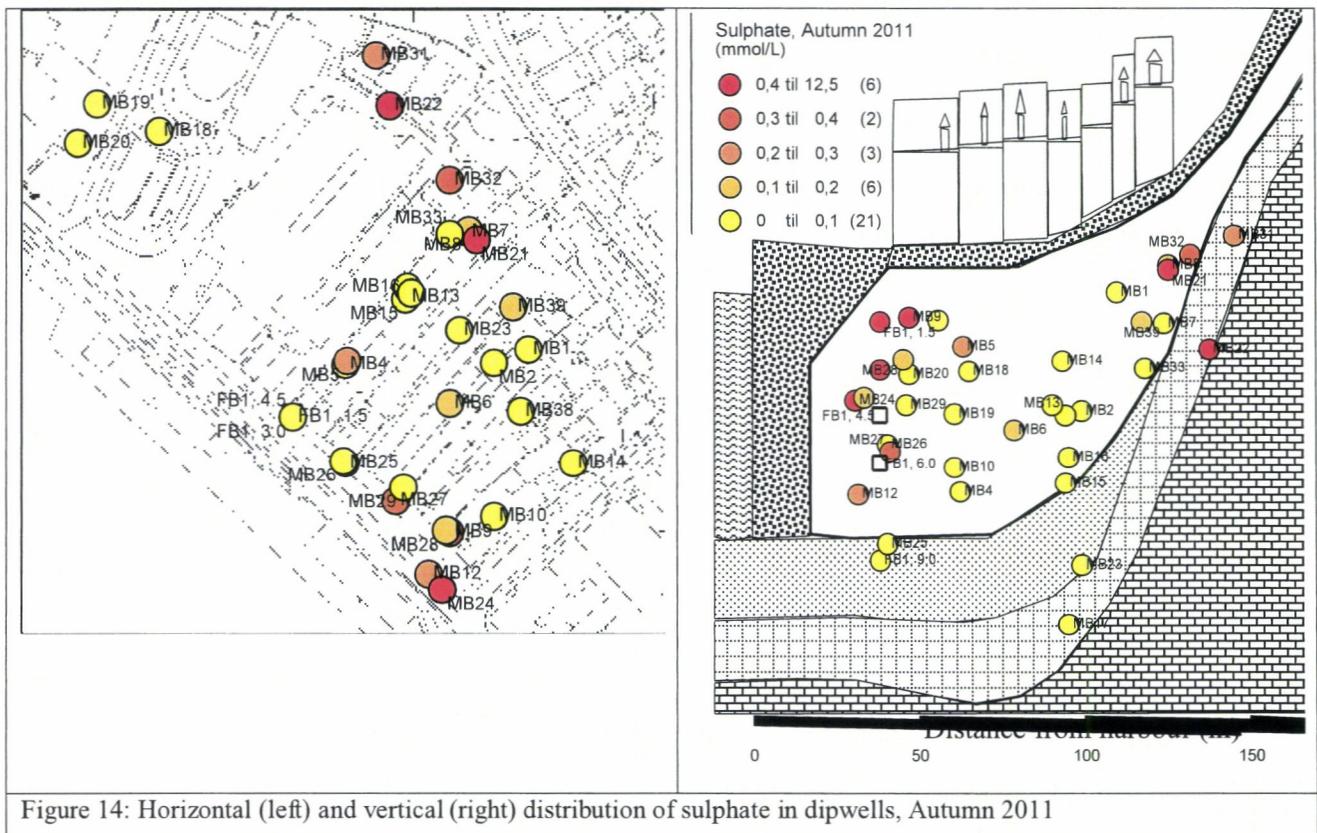


Figure 14: Horizontal (left) and vertical (right) distribution of sulphate in dipwells, Autumn 2011

Two “hotspots” for sulphate are indicated in Figure 14: at the harbour front and in the drained area at the back of Bryggen. The presence of sulphate at the harbour front is due to input of seawater as discussed above. As for the presence beneath the drained area, sulphate may be produced by the oxidation of different sulphur compounds in the unsaturated soil layers above, for instance when oxygen reacts with sulphur bound in organic matter or in different metal sulphides. Some of the sulphate produced may be dissolved and carried down into the saturated zone by infiltrating water, which means that drainage in an area may also influence the waterlogged deposits underneath. A similar pattern was observed at the archaeological site of Nydam in Denmark, where it was documented how a temporary drainage during an archaeological excavation influenced the sulphate concentration in a large area of the mire, even several months after the drainage had stopped (Matthiesen et al. 2004). The effect of sulphate on the decay of cultural deposits from Bryggen has recently been described in Hollesen and Matthiesen (2012).

As for the high concentrations of Fe^{2+} and Mn^{2+} beneath the drained area, they could stem from the reduction of iron and manganese oxides in the soil. In the unsaturated zone the conditions are quite dynamic and the presence of oxygen varies greatly depending on rainfall (Matthiesen and Hollesen 2012): In dry periods oxygen is present and may oxidise both organic material and different reduced species. In more wet periods oxygen is used up and other reactions take over. For iron compounds this may be illustrated by the two reactions:

Dry period: $O_2 (g) + 4 Fe^{2+}(aq) + 6 H_2O \rightarrow 4 FeOOH (s) + 8 H^+ (aq)$

Wet period: $4 FeOOH (s) + CH_2O (s) + 7 H^+ (aq) \rightarrow 4 Fe^{2+}(aq) + HCO_3^-(aq) + 5 H_2O$

where $CH_2O (s)$ represents organic matter. The dissolved $Fe^{2+} (aq)$ is mobile and may be transported by infiltrating water down into the saturated zone and the dipwells, whereas the iron oxide $FeOOH (s)$ is immobile and stays where it has precipitated. Similar reactions could be written for manganese species.

Overall, this indicates that during drainage different reactive species (sulphate, iron oxides and manganese oxides) may have accumulated in the unsaturated soil layers, where they participate in redox reactions. Some of the soluble species from the reactions (Fe^{2+} , Mn^{2+} and SO_4^{2-}) can be “exported” down into the saturated layers where they are found in the groundwater samples, whereas other (iron and manganese oxides) remain in the unsaturated layers. Even when the groundwater level has been raised in the area, it may take a period of time before all the oxidized species are reduced and optimal preservation conditions are fully re-gained. Relatively high concentrations of Fe^{2+} , Mn^{2+} and SO_4^{2-} have also been found in MB39 (orange symbols in Figure 14), which is placed in Bryggestredet outside the drained area. This could either indicate that drainage indirectly affects a larger area than expected or be due to local conditions around MB39 (Walpersdorf 2012).

It must be emphasized that this is only a hypothesis at this point, and it should be further investigated. The groundwater data from the drained area were characterised by a large error in the charge balance, that hasn't been unambiguously explained yet – thus the data should be interpreted with some caution. Furthermore, there are other dipwells (MB19 and MB28) with high Fe^{2+} contents that haven't been explained yet. Preliminary data from redox-measurements at different depths in the drained area have shown that precipitation has an almost immediate effect on the redox potential measured up to 1 m below the groundwater level (unpublished results from Michel Vorenhout, presented in Appendix 1 in Matthiesen and Hollesen 2012). This could support that there is an “export” of dissolved redox-active species from the unsaturated zone down into the groundwater– however, it still needs to be verified if this is due to a preferential flow path caused by the installation of the redox-probes or if it a general picture also for undisturbed deposits. Thus it is too early to categorise the preservation conditions in the waterlogged deposits beneath the drained area on the preservation condition scale (PresCon 1-5).

Conditions at harbour front and along sheet piling (B and C)

The conditions at the harbour front have recently been evaluated based on results from 2008 and from 8 sampling rounds in 2009 (Matthiesen 2010b). Here it was concluded that there is plenty of sulphate available in the upper porous soil strata in front of the buildings (MB9, MB24), and the preservation conditions are estimated to be poor to medium (PresCon 2-3). In 2011 the salt and sulphate concentrations in MB 24 were similar to earlier measurements, but in MB9 they were significantly lower. This could possibly be an effect of the renovation of the sewer system, reducing the input of seawater to the soil, but it is too early to say if the low concentrations in MB9 represent a permanent picture.

In the deeper soil strata and underneath the buildings (MB 26, 27, 28, 29) the soil is less porous, and the conditions less dynamic. The sulphate supply is limited to slow diffusion processes, thereby also limiting the sulphate reduction rate, and here the preservation conditions were estimated to be medium to good (PresCon 3-4) in Matthiesen (2010b). The samples from 2011 show similar contents of Na and Cl as in 2008 and 2009 in all 4 dipwells. However, the sulphate content has decreased in all the dipwells in 2011 (except MB27 where it is constant) indicating that there has been no new supply of sulphate to the layers in the years in between. Again this could possibly be an effect of the renovation of the sewer system. MB25 is placed in the natural deposits underneath the cultural layers – here the concentrations of Na and Cl have been increasing since 2008 which could indicate a changed flow pattern, but the sulphate concentrations are still very low. Overall, the conclusions from Matthiesen (2010b) are still considered valid.

The conditions at the sheet piling have recently been evaluated based on groundwater data from 2008 and 2009, which indicated that both the horizontal and the vertical water flow is significantly faster near the sheet piling compared to the central parts of Bryggen (Matthiesen 2010a). The conditions at MB5 were very dynamic, with frequent flushing of oxygen rich rainwater. The concentrations of dissolved ions in MB4, 7, 15, 32, 33 and FB1 (1.5 and 3.0) were relatively low, indicating some dilution by rainwater, whereas the concentrations in MB13 and MB16 were higher, indicating more stagnant conditions. The preservation conditions were estimated to be poor to medium (PresCon 2-3).

Looking at the 2011 data, they have corroborated the picture with increased water flow along the sheet piling. The concentrations in MB13 and MB16 are significantly lower than in 2008, which brings them in line with the rest of the dipwells along the sheet piling. The concentrations of most species are extremely low in MB33 in 2011, indicating a large rainwater influence – this may be due to the fact that the filter of MB33 is partly placed in a sand layer where the water flow may be fast. Overall, the conclusions from Matthiesen (2010a) are still considered valid, and the indications

of increased waterflow and dilution along the sheet piling has even become more clear with the decreased concentrations in MB13 and MB16 in 2011.

Conditions in the central, stagnant area (D)

The correlations between the species $\text{NH}_4^+ - \text{K}^+$, and $\text{NH}_4^+ - \text{HCO}_3^-$ observed for the 2005 samples (Matthiesen 2008b) and 2008 samples (Matthiesen 2009) are also present for the 2011 samples (Figure 15). These correlations have been taken as an indication that ammonium, potassium and bicarbonate mainly stem from the same source, namely decomposition of organic material.

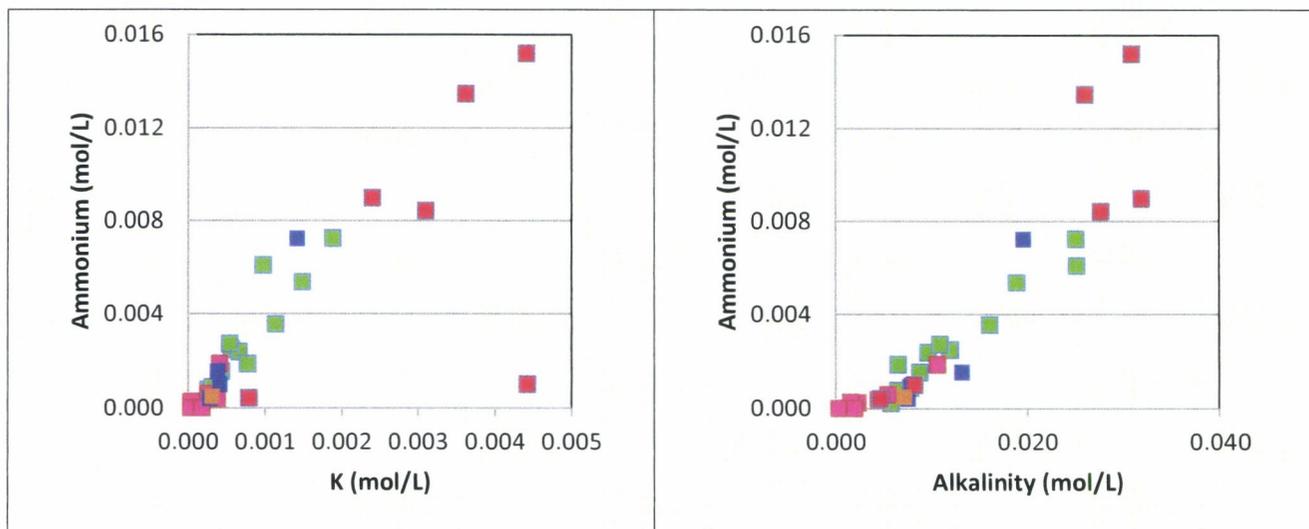


Figure 15: Correlation between $\text{K}-\text{NH}_4^+$ and between $\text{HCO}_3^- - \text{NH}_4^+$ in ground water samples from 2011. There is a distinct outlier in the $\text{K}-\text{NH}_4^+$ plot (MB24, where an input of seawater contributes to a high K concentration which was also the case in the 2008 sampling).

In 2008 a simple geochemical model was presented in an attempt to explain some of the observed ground water characteristics (Matthiesen 2009). The model suggests that decay of organic material is a key element in the groundwater formation, and it attempts to estimate a decay rate for the central area of Bryggen (the green area). The model considers an 8 m thick homogenous soil column, where the soil composition is based on the average content in >100 soil samples from Bryggen. Rainwater with a typical composition from Bergen (including dissolved oxygen, nitrate and sulphate) is added to the top of the column, and different redox reactions takes place down through the soil column. The downwards flow rate is estimated to 10 cm/year. The geochemical model is made in the software PHREEQC, which contains a thermodynamic database that calculates possible precipitation and dissolution processes. From this model the concentrations of different species in the groundwater at different depths is calculated. It is of course interesting if the model still gives a reasonable fit to the data, or if it has to be modified (Figure 16):

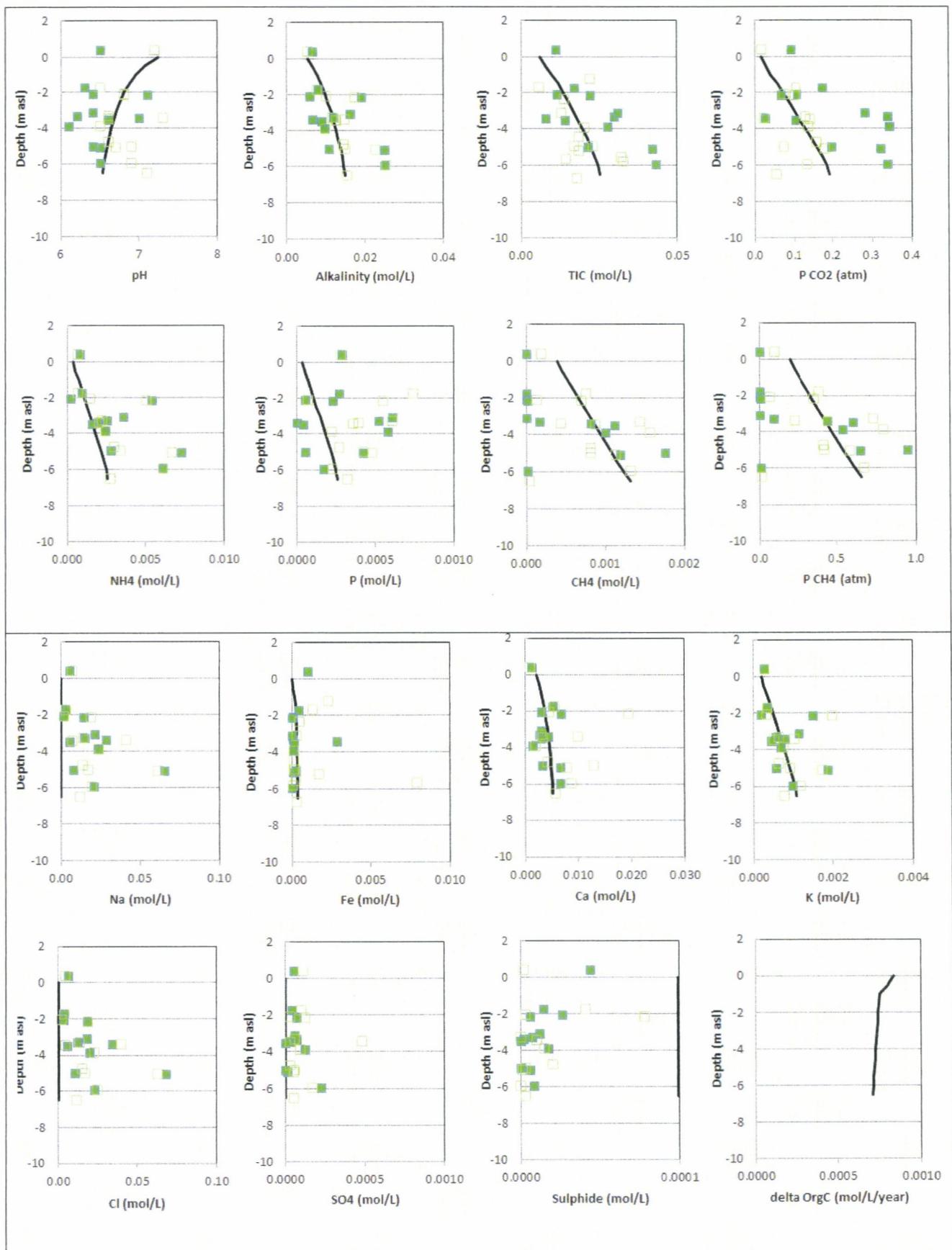


Figure 16: Numerical model for groundwater formation in central Bryggen (Area D). Model predictions are shown as black line, data from 2008 shown as open squares, and data from 2011 shown as filled squares.

For most species the measured concentrations are similar in 2008 and 2011, but there are also a few exceptions: For many of the dipwells pH is lower in 2011 compared to 2008 (upper left corner). This could possibly be a bias from the measurements, as pH was measured in the field in 2008, whereas in 2011 the samples were sent to the laboratory before measurements took place. The difference in pH will also influence the results for TIC (total inorganic carbon) and $P\text{ CO}_2$ (carbon dioxide partial pressure), as these are calculated from the pH and alkalinity of the samples. The CH_4 measurements also differ, as more dipwells show low concentrations in 2011, compared to 2008. Again, this could be a bias from the measurements, as some of this volatile analyte may have been lost during sampling in 2011, as mentioned earlier. There is a large variation in the concentrations of P (phosphorus) in 2008 and 2011, but none of the datasets show any clear trend. The alkalinity and the concentrations of NH_4^+ , K^+ , Ca^{2+} and Fe^{2+} are similar in 2008 and 2011, and the model gives a reasonable fit to both data sets. Furthermore the concentrations of Na^+ , Cl^- , SO_4^{2-} and sulphide are similar, but the model is too simple to fit these data sets, as it does not include a marine input.

Overall, the key parameters used for estimating decay rates for the organic material (especially bicarbonate, ammonium and potassium) are similar in 2008 and 2011, and the discussions and conclusions in Matthiesen (2009) are still considered valid. Thus, the preservation conditions in the deeper part of this central, stagnant area of Bryggen are still considered excellent (PresCon 5), even if there are indications of some input of sulphate from the drained area.

Temporal variation

Temporal variation in the chemical composition of ground water can be considered on 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 2006-2011 Hans de Beer from NGU installed automated loggers for

water table and temperature in fourteen dipwells. Out of these MB5, 11, 21 and 26 show short term (daily) temperature variation of a few degrees (de Beer 2008) which indicates dynamic conditions around the logger. MB2 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 7 degrees over a whole year in the different dipwells. The long term variation over several years will be evaluated by de Beer to document the effect of re-infiltration and a modified drainage system at the hotel.

Regarding the chemical analysis, repeated groundwater sampling has been made in 35 dipwells and piezometers (Figure 3-8, lower diagrams). Dipwells MB1 and MB2 were installed back in 2001, and the rest of the dipwells were included in the program as they were installed. Besides the results in Figure 3-8 samples were taken 8 times in 2009 from dipwells at the quayfront to study variations in Cl and SO₄ concentrations (Matthiesen 2010b). In Figure 3-8 most of the dipwells show a relatively low variation in the water composition over time, indicating fairly stable conditions. On the other hand, MB5 and 11 show a distinct variation in the water composition, and some variation in the concentrations of major ions is also observed in MB6, 7, 9, 13, 15, 16, 22, 25, 26, 27, 33 and FB1 (3 upper cells) as well:

MB5 and MB11 changes radically over time: MB5 varies between oxic and anoxic conditions (Figure 5 + 6) which fits well with the observations from the oxygen logger that showed very dynamic conditions where the water type changes weekly or daily depending on the amount of precipitation (Matthiesen 2005). The groundwater in MB11 is normally oxic to slightly reducing but shows a high variation in the SO₄²⁻, HCO₃⁻, Ca²⁺, NO₃⁻ and Fe²⁺ content (Figure 4-8).

MB9, 25, 26, 27 and FB1 are all placed at the harbour front. Some of them (except MB26 and 27) changes regarding the salt content (Figure 3) as was also shown in the detailed study at the harbour front from 2009 (Matthiesen 2010b). MB9 has shown a distinct freshening with a Cl content of only 42 mmol/L in 2011 (compared to hundreds mmol/L in 2009), possibly because flooding of the quay front area has become very rare after renovation of the sewer system. MB25, on the other hand, shows an increase in Cl content from 10 mmol/L in 2008 to 60 mmol/L in 2011, where the latter is in good correspondence with the results from 8 samplings 2009. The HCO₃⁻ concentration also increases from 5 to 20 mmol/L from 2008 to 2011, which is surprising as MB25 is placed very deep in the natural deposits beneath the cultural layer. MB26 and 27 show stable salt contents, but increasing HCO₃⁻ concentrations from 2008 to 2011 (Figure 7).

MB 7, 13, 15, 16, 22, 33 (and MB5) are placed along the sheet piling. MB 13, 16 and 33 show decreasing concentrations of Na^+ , Cl^- , Ca^{2+} , K^+ , NH_4^+ and HCO_3^- compared to 2008 (up to an order of magnitude) indicating an increased dilution. MB7 and MB15 show increased concentrations of Na and Cl, but modest variation for other species. MB22 shows a decrease in Na and Cl concentration and is generally characterised by slightly oxidising conditions as indicated by a high NO_3^- concentration (Figure 5). These variations are probably due to an increased water flow along the sheet piling (Matthiesen 2010a), i.e. the concentrations will depend on the precipitation in the days up to the ground water sampling.

MB 6 lies in the central Bryggen area, which has been considered relatively stable. None-the-less the Na^+ , Cl^- , NH_4^+ and HCO_3^- concentration in MB6 decreased by approximately 30% from the first analyses in 2003-05 to the analyses in 2008-11 (Figures 3, 4, and 7), while the concentrations of Fe^{2+} , Mn^{2+} and SO_4^{2-} increased (Figures 5 and 6). This could indicate that some of the “stagnant water” has been replaced by water from the “drained area”, as was also discussed for MB39. The concentrations seem to have reached a stable level during the last 3 sampling rounds (2008, 2009 and 2011).

Overall the data form an excellent basis for comparison with future ground water samples. Until now improved preservation conditions has only been observed in MB9 (by a reduced salt and SO_4 supply) but it will be very interesting to see if and how the ongoing mitigation work at the sheet piling will influence the ground water composition.

Conclusion and recommendations

The results from 40 groundwater samples from the autumn 2011 have been presented and commented on in terms of preservation conditions in the waterlogged cultural deposits on Bryggen.

- The results from the ground water sampling and chemical analyses are generally consistent and considered of acceptable quality, even if there were some problems with solid particles in several samples, a bad ion-balance in some samples, and possible loss of methane from other samples
- The results have confirmed and refined the earlier established conceptual model for groundwater chemistry and -formation on Bryggen
- The indications of an increased water flow along the sheet piling have been strengthened. At the sampling in 2008 the results from dipwells MB13 and MB16 indicated relatively stagnant conditions, but at the sampling in 2011 also these two dipwells showed an increased dilution, similar to the rest of the dipwells along the sheet piling.
- At the quay front area there are signs of improved preservation conditions at MB9 during the monitoring period, as salt and sulphate concentrations has decreased significantly since 2009. This may be an effect of the restoration of the sewer system
- New knowledge has been obtained about the drained area, where it has been demonstrated how processes in the unsaturated soil layers may influence the conditions in the waterlogged layers underneath by increased concentrations of Fe^{2+} , Mn^{2+} and SO_4^{2-} in the groundwater.
- There are indications that these processes may also affect groundwater outside the drained area, but it is too early to evaluate the exact consequences for the preservation conditions

Future work with groundwater sampling should include

- The data should be further evaluated in a combined hydrological-geochemical model
- The sampling procedure should be adjusted to reduce bias on future results
- Samples for partial analysis should be taken frequently in the drained area and along the sheet piling during the mitigation work at Bryggen
- Oxygen probes should be installed in a few dipwells along the sheet piling to document if it is possible to reduce the water flow
- New samples should be taken in all dipwells in 3-5 years time when the mitigation work is finished

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Appendix 1

Results from chemical analysis of ground water samples taken autumn 2011. No measurements were taken during sampling.

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) are available upon request.

		MB1	MB2	MB4	MB5	MB6	MB7	MB8	MB9	MB10	MB11	MB12	MB13	MB14	MB15
x		297519.751	297507.633	297454.210	297454.986	297491.299	297499.567	297500.197	297489.592	297505.547	297606.297	297481.388	297477.469	297534.297	297476.607
y		6701336.513	6701331.949	6701333.198	6701334.655	6701318.164	6701377.659	6701378.33	6701272.658	6701277.855	6701364.945	6701258.540	6701355.873	6701295.773	6701355.22
Distance to harbour (m)		111	100	62	63	79	126	127	46	60	193	30	95	94	95
Dipwell top (m asl)		2.78	2.18	1.62	1.67	1.62	4.21	4.26	1.65	1.42	16.91	1.12	1.94	2.28	1.91
Filter top (m asl)		1.90	-1.80	-4.88	-0.30	-2.38	0.46	2.26	0.65	-3.58	14.81	-3.45	-0.95	-0.74	-5.09
Filter bottom (m asl)		-1.10	-4.80	-6.88	-2.30	-5.38	-1.54	0.26	-1.35	-6.58	9.81	-8.45	-5.95	-2.74	-6.09
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		06-09-2011	06-09-2011	06-09-2011	06-09-2011	06-09-2011	02-09-2011	02-09-2011	29-08-2011	29-08-2011	06-09-2011	31-08-2011	02-09-2011	06-09-2011	02-09-2011
Water level (m asl)		2.29	1.33	0.59	0.62	1.18	1.29	2.03	0.40	0.57	12.35	0.48	0.65	1.70	0.63
Parameter	weight	Unit: mmol/L													
Na ⁺	22.99	5.65	14.79	6.96	0.87	23.49	3.09	4.78	28.71	65.25	0.65	20.44	0.31	3.09	7.39
K ⁺	39.10	0.26	0.56	0.26	0.15	0.66	0.16	0.26	0.79	1.87	0.05	0.97	0.04	0.31	0.41
Ca ⁺⁺	40.08	1.22	2.74	1.62	1.17	1.55	2.00	6.24	0.95	6.49	0.85	6.49	0.50	5.24	2.99
Mg ⁺⁺	24.31	0.34	0.82	0.39	0.32	0.66	0.30	0.62	1.93	1.56	0.09	2.63	0.04	0.82	0.66
Mn ⁺⁺	54.94	0.03	0.01	0.01	0.01	0.00	0.01	0.09	0.00	0.01	0.00	0.00	0.00	0.02	0.01
Fe ⁺⁺	55.85	1.02	0.06	0.20	0.66	0.07	0.06	3.22	0.13	0.06	0.06	0.02	0.06	0.45	0.05
NH ₄ ⁺	18.04	0.78	2.49	0.61	0.02	2.38	0.19	0.09	0.43	7.21	0.00	6.10	0.25	0.89	1.88
Cl ⁻	35.45	5.92	12.13	5.08	0.68	19.46	3.95	3.38	42.31	67.70	0.85	22.85	0.99	3.95	5.36
SO ₄ ⁻⁻	96.06	0.05	0.07	0.08	0.21	0.12	0.01	0.14	0.88	0.01	0.10	0.22	0.07	0.04	0.01
NO ₃ ⁻	62.01	0.00	0.00	0.01	0.04	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.02	0.00	0.00
P-tot	30.97	0.29	0.52	0.15	0.00	0.58	0.18	0.30	0.05	0.42	0.02	0.17	0.02	0.27	0.29
HS ⁻	32.06	0.04	0.01	0.00	0.00	0.02	0.01	0.00	0.02	0.01	0.00	0.01	0.00	0.01	0.00
HCO ₃ ⁻	61.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O ₂	31.9988							0.11			0.14		0.17		
CH ₄	16.042	0.00	0.17	0.00	0.00	1.00	0.00	0.00	0.00	1.18	0.00	0.01	0.00	0.00	0.01
pH		6.5	6.2	6.1	6.4	6.1	6.6	6.5	6.5	6.5	6.8	6.5	6.3	6.3	6.2
Conductivity (mS/m)															
Dry weight (mg/L)		620	1400	640	170	1800	580	710	2700	5100	140	2500	190	710	860
Colour															
Temperature (°C)															
Comments from laboratory		Precipitate in sample for metals	Precipitate in sample for metals	Precipitate in sample for metals	Precipitate in sample for metals	Precipitate in sample for metals	Sulfide sample not filled	Sulfide sample not filled	Precipitate in sample for metals	Precipitate in sample for metals	Precipitate in sample for metals	Precipitate in sample for metals	Sulfide sample not filled	Precipitate in sample for metals	Sulfide sample not filled
Sum cations (meq/L)		11.92	25.11	12.27	5.37	31.10	8.19	25.46	35.96	90.57	2.71	45.80	1.81	17.34	17.11
Sum anions (meq/L)		12.80	24.65	10.84	2.22	29.90	8.50	13.08	48.82	93.05	2.32	48.54	3.51	12.09	16.28
Diff cat-an		-0.88	0.46	1.42	3.15	1.20	-0.32	12.38	-12.87	-2.48	0.38	-2.74	-1.70	5.25	0.83
Relativ diff (%)		-4%	1%	6%	41%	2%	-2%	32%	-15%	-1%	8%	-3%	-32%	18%	2%

	MB16	MB17	MB18	MB19	MB20	MB21	MB22	MB23	MB24	MB25	MB26	MB27	MB28	MB29	
x	297477.481	297478.496	297390.821	297369.305	297361.722	297502.868	297473.095	297495.436	297486.335	297453.172	297452.34	297470.672	297488.494	297473.319	
y	6701359.292	6701357.441	6701416.415	6701426.534	6701413.659	6701375.140	6701422.672	6701344.008	6701252.996	6701298.498	6701299.369	6701283.982	6701273.696	6701289.209	
Distance to harbour (m)	96	96	65	60	46	127	140	100	29	39	39	40	44	45	
Dipwell top (m asl)	2.14	2.13	2.9	2.54	1.24	4.11	4.67	1.98	1.22	1	0.97	0.93	1.785	0.88	
Filter top (m asl)	-4.26	-9.49	-1.58	-2.90	-1.65	1.61	-0.88	-7.12	-2.46	-6.96	-3.86	-4.07	-1.22	-2.62	
Filter bottom (m asl)	-5.26	-10.49	-2.58	-3.90	-2.65	0.61	-1.88	-9.12	-3.46	-7.96	-4.86	-5.07	-2.22	-3.62	
Natural deposit (m asl)			-2.90		-2.50		0.75	-5.50		-8.25			-8.10	-7.00	
Rock (m asl)	-3.90				-2.55										
Sampling date	02-09-2011	02-09-2011	07-10-2011	29-08-2011	29-08-2011	02-09-2011	07-10-2011	06-09-2011	31-08-2011	31-08-2011	31-08-2011	31-08-2011	29-08-2011	29-08-2011	
Water level (m asl)	0.53	0.58	0.66	2.49	-0.70	1.84	1.14	0.66	-0.01	0.37	0.38	0.29	0.72	-0.15	
Volume pumped (L)															
Parameter	weight	Unit: mmol/L													
Na ⁺	22.99	0.78	2.48	2.00	28.27	14.35	3.44	0.57	5.22	226.19	39.15	113.09	165.29	134.84	204.44
K ⁺	39.10	0.05	0.28	0.18	0.77	1.48	0.31	0.09	0.38	4.35	1.41	2.38	3.58	3.07	4.35
Ca ⁺⁺	40.08	0.32	2.99	2.99	4.24	6.74	6.24	1.87	3.99	6.24	11.48	3.24	9.98	7.98	10.48
Mg ⁺⁺	24.31	0.12	0.33	0.23	1.89	1.36	0.78	0.30	0.62	25.10	1.36	3.70	6.58	6.17	4.53
Mn ⁺⁺	54.94	0.00	0.01	0.00	0.02	0.01	0.05	0.01	0.00	0.00	0.04	0.00	0.00	0.03	0.01
Fe ⁺⁺	55.85	0.17	0.05	0.06	2.86	0.02	1.59	0.29	0.12	0.01	0.36	0.41	0.00	2.33	0.82
NH ₄ ⁺	18.04	0.28	0.41	0.22	1.88	5.38	0.03	0.03	1.55	1.00	7.21	8.87	13.31	8.32	14.97
Cl ⁻	35.45	1.86	2.03	3.10	33.85	18.62	1.66	0.56	3.10	282.06	56.41	118.47	174.88	138.21	220.01
SO ₄ ⁻⁻	96.06	0.06	0.00	0.07	0.02	0.07	0.42	1.15	0.01	12.49	0.01	0.01	0.35	0.16	0.01
NO ₃ ⁻	62.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P-tot	30.97	0.01	0.13	0.05	0.00	0.23	0.05	0.03	0.27	0.06	0.01	0.48	0.31	0.00	0.04
HS ⁻	32.06	0.01	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.81	0.01
HCO ₃ ⁻	61.02	1.62	7.52	5.72	6.47	18.85	5.97	2.23	13.11	8.05	19.50	31.63	25.73	27.37	30.48
O ₂	31.9988														
CH ₄	16.042	0.02	0.01	0.00	0.81	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.15	0.69	0.50
pH		6.1	6.8	6.4	7	7.1	6.5	6.2	6.6	6.5	6.5	6.5	6.4	6.6	6.6
Conductivity (mS/m)															
Dry weight (mg/L)	130	530	680	2900	2100	470	740	870	24000	5000	7700	12000	10000	15000	
Colour															
Temperature (°C)															
Comments from laboratory	Sulfide sample not filled	Sulfide sample not filled		Precipitate in sample for metals	Precipitate in sample for metals	Sulfide sample not filled		Precipitate in sample for metals	Precipitate in sample for metals	Precipitate in sample for metals	Precipitate in sample for metals	Precipitate in sample for metals	Precipitate in sample for metals	Precipitate in sample for metals	Precipitate in sample for metals
Sum cations (meq/L)	2.36	9.94	8.98	48.96	37.46	21.09	5.64	16.62	294.23	74.23	139.07	215.31	179.26	255.43	
Sum anions (meq/L)	3.62	9.69	9.03	40.36	37.85	8.51	5.12	16.50	315.16	75.95	150.61	201.64	166.70	250.56	
Diff cat-an (meq/L)	-1.27	0.24	-0.05	8.59	-0.38	12.58	0.52	0.12	-20.93	-1.72	-11.55	13.67	12.56	4.87	
Relativ diff (%)	-21%	1%	0%	10%	-1%	42%	5%	0%	-3%	-1%	-4%	3%	4%	1%	

	MB31	MB32	MB33	MB34	MB35	MB38	MB39	FB1, 1.5	FB1, 3.0	FB1, 4.5	FB1, 6.0	FB1, 9.0		
x	297469.206	297493.798	297492.885	297578.49	297609.4	297516.33	297514.87	297435.437	297435.437	297435.437	297435.437	297435.437		
y	6701440.708	6701395.983	6701377.098	6701153.64	6701153.89	6701314.83	6701351.31	6701315.099	6701315.099	6701315.099	6701315.099	6701315.099		
Distance to harbour (m)	148	134	120	32	55	91	119	37	37	37	37	37		
Dipwell top (m asl)	6.65	4.54	3.33	2.18	1.93	2.40	3	1	1	1	1	1		
Filter top (m asl)	2.65	2.04	-1.49	-2.39	0.03	-2.60	0.00	-0.50	-2.00	-3.50	-5.00	-8.00		
Filter bottom (m asl)	1.65	1.04	-2.49	-3.39	-0.97	-3.60	-1.00	-0.50	-2.00	-3.50	-5.00	-8.00		
Natural deposit (m asl)	2.70	0.30		-3.80	-1.95			-8.40	-8.40	-8.40	-8.40	-8.40		
Rock (m asl)	-1.00													
Sampling date	10-10-2011	02-09-2011		31-08-2011	31-08-2011	22-12-2011	07-10-2011	05-09-2011	05-09-2011	05-09-2011	05-09-2011	05-09-2011		
Water level (m asl)	3.68	2.28	1.41	0.52	0.97		2.58							
Volume pumped (L)														
Parameter	weight	Unit: mmol/L												
Na ⁺	22.99	0.33	1.22	0.08	3.13	21.75	21.31	1.22	1.00	8.26	5.22	7.83	4.13	
K ⁺	39.10	0.16	0.31	0.04	0.24	0.51	1.13	0.31	0.18	0.38	0.43	0.54	0.41	
Ca ⁺⁺	40.08	1.55	3.74	0.25	2.25	5.74	2.99	5.74	1.37	1.90	2.99	3.24	2.50	
Mg ⁺⁺	24.31	0.29	0.62	0.12	0.20	0.66	1.15	0.95	0.18	0.66	0.70	0.74	0.66	
Mn ⁺⁺	54.94	0.02	0.03	0.01	0.00	0.02	0.00	0.06	0.00	0.00	0.01	0.01	0.01	
Fe ⁺⁺	55.85	1.34	1.79	0.36	0.05	1.00	0.03	1.24	0.07	0.03	0.12	0.27	0.11	
NH ₄ ⁺	18.04	0.07	0.06	0.01	0.12	1.72	3.55	0.50	0.00	0.39	1.55	2.72	1.00	
Cl ⁻	35.45	0.20	1.33	0.11	3.10	26.23	17.77	1.41	0.65	7.05	5.64	10.15	4.51	
SO ₄ ⁻⁻	96.06	0.27	0.33	0.03	0.16	0.01	0.06	0.18	0.76	0.91	0.00	0.00	0.01	
NO ₃ ⁻	62.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	
P-tot	30.97	0.00	0.02	0.01	0.05	0.04	0.61	0.12	0.01	0.05	0.04	0.05	0.04	
HS ⁻	32.06	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.00	0.01	0.00	0.00	0.00	
HCO ₃ ⁻	61.02	2.15	4.56	0.41	5.00	9.08	16.03	7.10	1.98	4.46	8.75	10.83	7.87	
O ₂	31.9988					0.05								
CH ₄	16.042	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.13	1.12	1.75	0.37	
pH		6.4	7	6.4	6.8	6.5	6.4	6.4	7.3	7	6.6	6.4	6.9	
Conductivity (mS/m)														
Dry weight (mg/L)	280	490	31	500	2300	1900	1400	260	950	770	1000	650		
Colour														
Temperature (°C)														
Comments from laboratory			Sulfide sample not filled	Precipitate in sample for metals	Precipitate in sample for metals			Precipitate in sample for metals. Sulfide sample not filled	Precipitate in sample for metals. Sulfide sample not filled	Precipitate in sample for metals. Sulfide sample not filled	Precipitate in sample for metals. Sulfide sample not filled	Precipitate in sample for metals. Sulfide sample not filled		
Sum cations (meq/L)	6.98	13.95	1.61	8.49	38.83	34.34	18.00	4.43	14.21	14.84	19.61	12.08		
Sum anions (meq/L)	2.89	6.57	0.60	8.47	35.39	34.54	9.00	4.26	13.37	14.44	21.04	12.45		
Diff cat-an (meq/L)	4.09	7.37	1.01	0.03	3.44	-0.21	9.00	0.17	0.83	0.41	-1.42	-0.37		
Relativ diff (%)	41%	36%	46%	0%	5%	0%	33%	2%	3%	1%	-3%	-1%		