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Title:
Preservation conditions in unsaturated urban deposits: Results from continuous logging of oxygen, water content and temperature at the rear of Nordre Bredsgården, Bergen in the period October 2010 to November 2011

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Summary:

The present report focuses on environmental monitoring in unsaturated urban deposits. The study takes place at the rear of Nordre Bredsgården, Bryggen, where the groundwater level is low and the upper 3 m of the deposits are unsaturated. The soil surface settles by 6-8 mm/year in this area, probably due to degradation of organic material in the soil. Results from continuous logging of oxygen, water content and temperature in the ground are presented, and discussed in terms of what controls the oxygen supply and decay in the ground, and what can be done to reduce the decay rates. Data from measurements of redox potential in the soil were received after the main report was finished, but the raw data are shown in an appendix.

The results show that oxygen is mainly found in the upper 1 m of the soil profile, and occasionally in a coarse gravel layer deeper down, which corroborates the results from excavations in 2006 and 2010 excavations, and in situ decay studies with modern wood samples.

The results demonstrate a strong correlation between the precipitation, the water content and the oxygen concentration in the soil: During long dry periods, the water content of the soil layers decreases, and oxygen penetrates deeper into the soil, and when it rains the water content of the soil increases and the oxygen concentration decreases. The effect of oxygen dissolved in rainwater is debated, and the results show that even during heavy rain the oxygen concentrations in the unsaturated zone decrease rather than increase.

In terms of remediation actions it is important to know “how wet is wet enough” to keep the deposits anoxic. The first results indicate that free oxygen appears in the soil when the air content of a soil layer (i.e. the porosity minus the water content) exceeds approximately 5-15% vol, but the estimate needs to be further validated with longer monitoring periods and in other soil types. When validated, such an estimate may be used to interpret water content data from the previous years (before the oxygen logger was installed) and possibly also from other sites where water content loggers are installed.

The decay rate for a given soil layer depends both on the oxygen supply and on the reactivity of the soil. The reactivity has been estimated for a few soil layers by measuring the oxygen consumption rate in the laboratory. The rate varies by a factor 5-10, with the deepest soil layers being most reactive.

The first data indicate that the soil layers at 3-3.5 m asl are most prone to decay. There were a few long dry periods during the first year of monitoring where oxygen penetrated deeper into the soil, however it is too early to say if decay during these dry periods is more important than during the rest of the year.

The decay of organic material by other oxidants (such as nitrate, sulphate, iron and manganese oxides) in the unsaturated zone has not been quantified, but their effect is estimated to be less important compared to oxygen.

The observations need to be validated by continued monitoring at the site, especially during extreme events such as long dry periods. The conditions are very dynamic and with a significant temporal variation, which can make it a challenge to isolate and document the effect of different mitigation actions on a short time scale. It is recommended to upgrade the current 4-channel oxygen meter to a 10 channel meter, in order to make measurements simultaneously at all depths. Furthermore, it is recommended to install new water content sensors (Profile Probe) in the upper soil layers, in order to replace sensors that have failed.

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Introduction

Measurements at Bryggen have shown that the buildings and soil surface at the Bredsgården and Bugården tenement are settling at a considerable rate – up to 6-8 mm/year (Jensen 2007). This settling is most likely a consequence of a lowered groundwater table in the area, giving an increased oxygen access and increased decomposition of organic material in the soil.

In September 2006 a 2½-metre deep testpit was opened at the northern end of Bredsgården (Figure 1) in order to assess the state of preservation of the deposits (Dunlop 2007). Field measurements were made in order to investigate the preservation conditions, and modern wood samples and water content sensors were installed in the unsaturated zone above the groundwater level (Matthiesen 2007). The report from 2007 contains a theoretical discussion on oxygen dynamics and how measurements of oxygen, porosity and water content in the soil may be used to estimate oxygen supply and decay rates. Some of the results have been published in Matthiesen et al. (2008), and results from monitoring of water content were described in Matthiesen (2010). The testpit was re-opened in October 2010 in order to install supplementary monitoring equipment, to retrieve the wood samples for analysis, and to evaluate any changes in the state of preservation of the cultural layers (Matthiesen and Hollesen 2011). The modern wood samples showed fungal attack and a decreased density for samples down to approximately 2.4 m asl, and less attack for deeper lying samples. There was a slight decrease in organic content of one of the upper soil layers in the period 2006-2010, but due to the heterogeneity of the soil it was difficult to make any firm conclusions.

In 2011 work is initiated to improve the preservation conditions at Bryggen by raising the ground water level and increasing the infiltration of rainwater. This makes it necessary to address several questions:

- What is the exact correlation between oxygen, water content and precipitation? – will an increased water content in the soil always reduce the oxygen supply, or can oxygen dissolved in rainwater actually increase the supply?
- Where and when does the decay take place? – is it mainly in the upper soil layers and mainly in dry periods/years?
- How wet is wet enough to keep the deposits anoxic?
- Is oxygen the main cause of decay, or are other oxidants equally important?
- Can we document the effect of different remediation actions, such as an increased drainage level or local re-infiltration?

The questions cannot be fully answered yet, but this report describes the results from the first year of continuous logging of oxygen, water content and temperature in the testpit. The theoretical background is described in Matthiesen (2007) and is not repeated here. The project has been funded by Riksantikvaren (the Norwegian Directorate for Cultural Heritage).

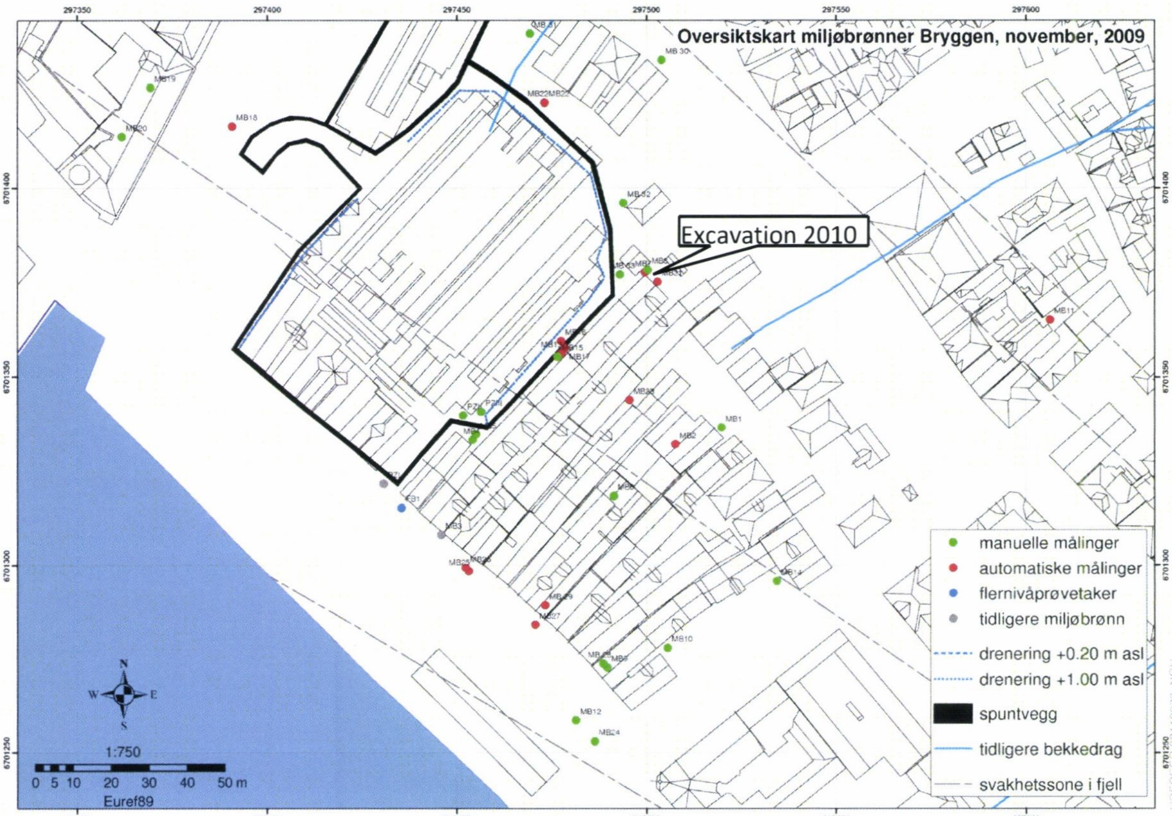
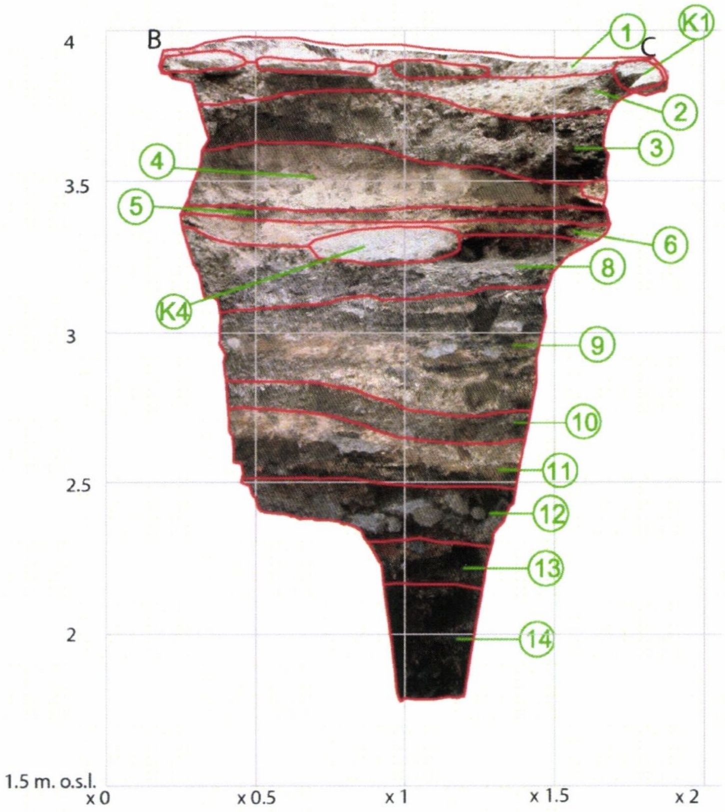


Figure 1: Map of Bryggen, showing the excavation site at the northern end of Bredsgården, along with dipwells and drillings. Dotted blue line shows a drain pipe, which lowers the groundwater level locally.

Site and methods

The soil stratigraphy in the testpit is shown in Figure 2 (photo from the excavation in 2006), which is described in detail in Matthiesen (2007) and Dunlop (2007). Installation of oxygen, water content and temperature sensors in the re-opened testpit in 2010 is described in Matthiesen and Hollesen (2011) and the installation depth of the different sensors is given in Table 1. The average loss on ignition and the porosity of soil samples taken at the water content sensors is also given (from Figure 5 and Table 2 in Matthiesen & Hollesen (2011)). The sensors were placed approximately 1 m away from the profile shown in Figure 2, so there are some minor differences between the layer description and heights in Figure 2 and in Table 1.



Brief description of soil strata:
1: demolition/levelling deposit
2: sand w. gravel and pebbles
3: mixed layer, sandy w. decayed wood
4: fine sand ("Dutch ballast sand")
5: humus w. some thin planks
6: fine sand ("Dutch ballast sand")
8: organic-rich sandy layer w. timber
9: Alternating layers of lime, charcoal and stone
10: mixture of sand and lime
11: lime, very fine grained
12: sandy, porous layer w. stones at the bottom
13: firelayer, red w. sand in upper part, black with charcoal in lower part
14: organic layer, with timbers

Figure 2: North-east profile of testpit excavated in 2006. Each individual soil layer has been thoroughly described by archaeologist Rory Dunlop (2007) using a standardized layer recording system. An ultra-short description of the layers is given to the right.

m asl	Water content	Oxygen	Temperature	Soil layer	Loss on ignition (%)	Porosity (% vol)
4.14				Soil surface		
4.12			Temp 1	Cobblestone		
3.92	SM200-4	Oxy 2	Temp 2	Sand	0	39
3.68		Oxy 3	Temp 3	Backfill		
3.60	SM200-3**			Backfill		
3.46		Oxy 4	Temp 4	Backfill		
3.31	SM200-2*	Oxy 1		Dutch sand (#6)	2	45
3.21		Oxy 5	Temp 5	Backfill		
3.09	Theta 1			Organic (#8)	20	62
3.06		Oxy 6	Temp 6	Organic (#8)		
2.77	Theta 2	Oxy 7	Temp 7	Lime/sand (#9/10)	6	71
2.50		Oxy 8	Temp 8	Lime (#11)		
2.37	Theta 3			Gravel (#12)	3	43
2.31		Oxy 9	Temp 9	Gravel (#12)		
2.00	Theta 4	Oxy 10		Organic (#14)	35	80

Table 1: Heights above sea level (m asl) of sensors. Numbers in the column "soil layer" refer to the layer numbers in Figure 2. Soil porosity was measured in soil samples taken right next to the water content sensors, while loss on ignition are average values for the soil layer. *: this sensor was disconnected in March 2011, ** this sensor was disconnected in May 2011.

During the installation of the monitoring equipment samples were taken to analyse the reactivity of the soil material at different temperatures and different water contents in the laboratory. These measurements are described in Hollesen and Matthiesen (2011b and 2011a). Furthermore, samples of modern wood had been placed in the soil in 2006 and re-trieved in 2010 to study the decay rate in situ – the analyses and results are described in Matthiesen and Hollesen (2011).
Other data used in this report include water level measurements from dipwell MB7 and MB21 next to the testpit (methodology described in de Beer (2008), and measurements of water content in four different soil layers in the period 2006-2010 (installation described in Matthiesen (2007)). Furthermore precipitation data from the metrological station Florida in Bergen has been used (available from www.met.no). Sensors for measurement of redox potential were installed by Michel Vorenhout in May 2011 (Vorenhout 2011); the data were received too late to be fully incorporated in this report, but some of the initial data are shown in Appendix 1.

Results

Logging period and data availability

The monitoring of oxygen, water content and temperature was initiated in October 2010, and Table 2 describes the different changes and events in the monitoring up to November 2011.

Period	Water content (m asl)	Oxygen sensor (m asl)	Temperature
29/10/10 – 1/1/11	3.92, 3.60, 3.31, 3.09, 2.77, 2.37, 2.00	3.21, 3.06, 2.77, 2.50	All
1/1/11 – 23/1/11	None (short circuit)	3.21, 3.06, 2.77, 2.50	None
23/1/11 – 17/3/11	None (short circuit)	none	None
17/3/11 – 9/5/11	3.92, 3.60, 3.09, 2.77, 2.37, 2.00	3.21, 3.06, 2.77, 2.50	All
9/5/11 – 19/5/11	3.92, 3.60, 3.09, 2.77, 2.37, 2.00	3.21, 3.06, 2.31, 2.00	All
19/5/11 – 26/8/11	3.09, 2.77, 2.37, 2.00	3.21, 3.06, 2.31, 2.00	All
26/8/11 – 1/9/11	3.09, 2.77, 2.37, 2.00	none	All
1/9/11 – 14/11/11	3.92, 3.09, 2.77, 2.37, 2.00	3.92, 3.31, 3.21, 3.06	All
14/11/11 - today	3.92, 3.09, 2.77, 2.37, 2.00	3.68, 3.46, 3.21, 3.06	All

Table 2: Data availability for different sensors in different periods.

Only four oxygen sensors may be connected to the data logger at a time, so the ten oxygen sensors are exchanged at intervals. In the period 1st of January to the 17th of March one of the water content sensors short circuited and caused the datalogger to shut down on the 23rd of January. This was repaired on the 17th of March. On the 9th of May data was downloaded and logging was initiated on two new oxygen sensors. On the 19th of May two water content sensors were disconnected because one of them had become unstable. On the 26th of August the oxygen meter temporarily stopped logging. On the 1st of September the oxygen meter was restarted, logging was initiated on two new oxygen sensors, and one water content sensor was reconnected. On the 28th of November the latest data for this report were downloaded.

Water content

Water content measured in the different soil layers is shown in Figure 3.

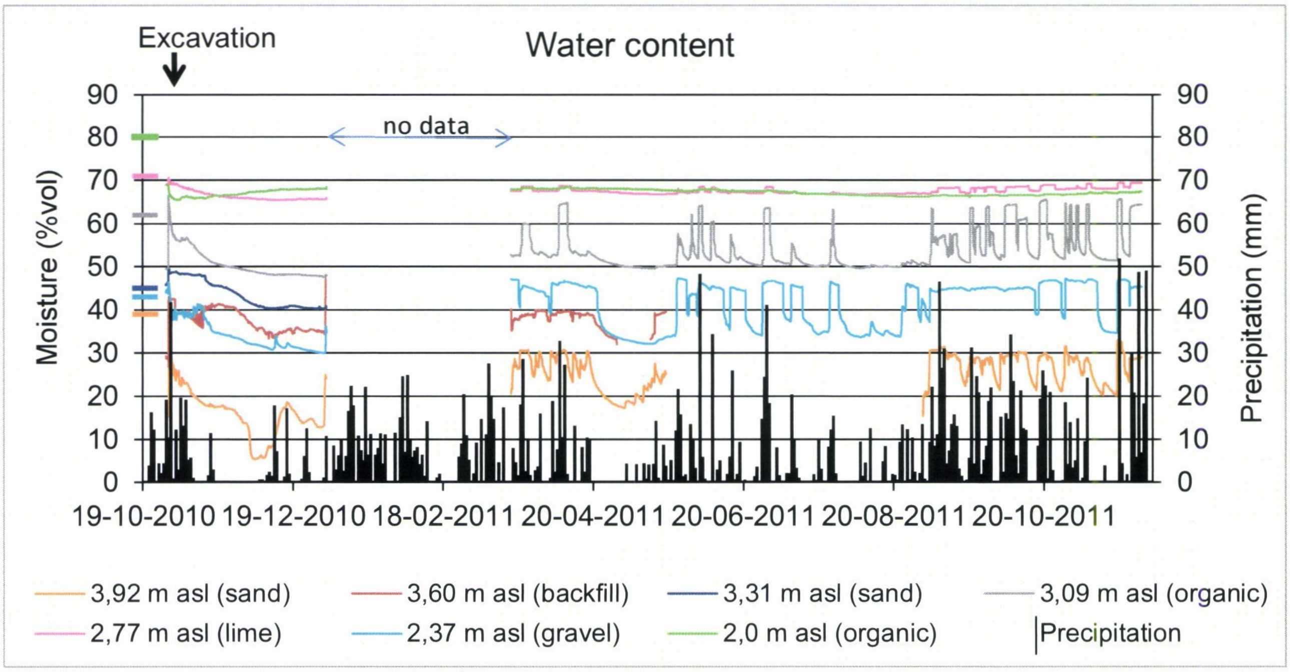


Figure 3: Results from water content probes. The soil porosity, as measured in ring samples in the laboratory, is shown with horizontal lines to the left (on y-axis). No ring sample could be taken from the soil layer at 3.60 m asl. Precipitation data from met.no are shown as black columns (station Bergen, Florida)

The results for each individual sensor and soil layer are discussed in detail below. However, as a general picture it is observed for the period October 2010 to November 2011 that:

- There is an initial phase just after the installation where water contents are high, probably because of disturbance of the system by backfilling the excavation pit.
- There is a dry period in 17/11-11/12 2010 where the water content values decreases for all sensors (except at 2.00 m asl)
- There is a dry period 19/4-2/5 2011 where the water content values decreases for all sensors, and for some sensors the decrease even continues to the middle of May.
- There is a clear correlation between the precipitation and the water content of the soil.

Ground water level measured in MB21 and MB7 for the same period are presented in Figure 4. The two dipwells are both placed less than two meters from the testpit, with MB7 on the north-west side (between the testpit and the sheet piling) and MB21 on the south-east side (closest to the water content and oxygen sensors). MB7 has its filter from -1.54 to 0.46 m asl, and MB21 has its filter from 0.61 to 1.61 m asl, i.e. deeper than the water content probes described above.

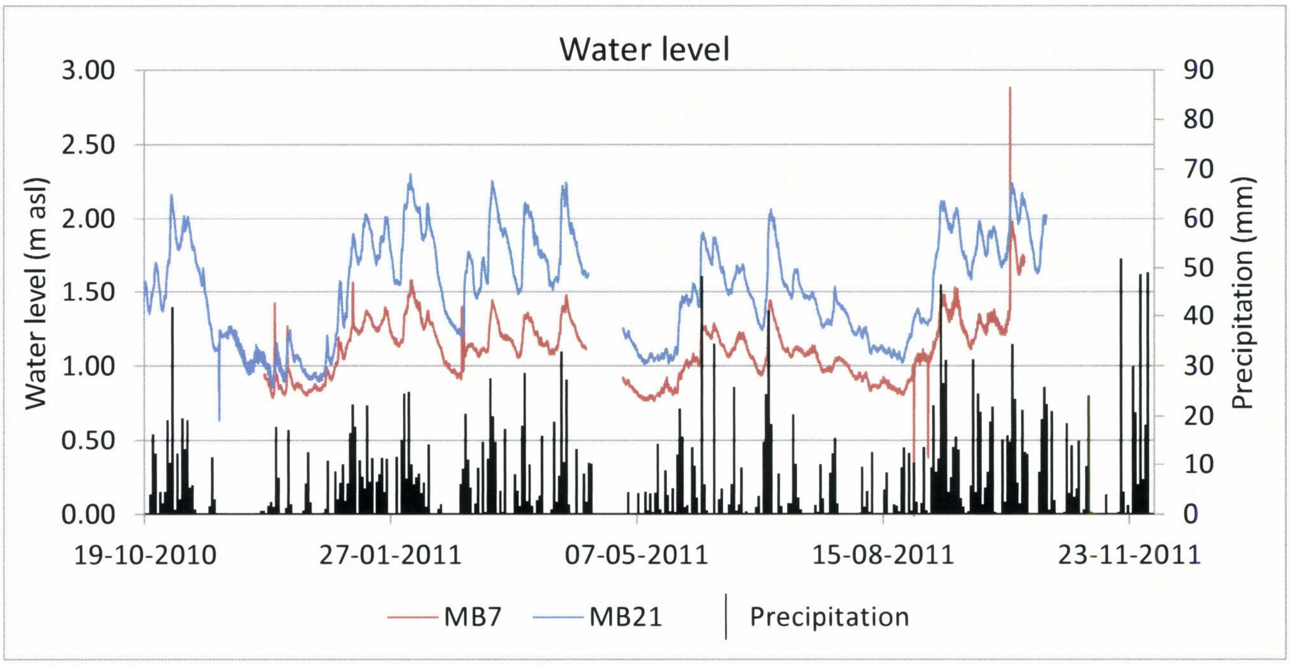


Figure 4: Ground water level measured in MB7 and MB21 next to the testpit. Data from Hans de Beer, Norwegian Geological Survey.

The ground water level is shown for reference and will not be discussed in any detail. However, a few points are relevant for the interpretation of the water content and oxygen measurements in the unsaturated zone:

- There is a clear correlation between the ground water level and the precipitation, as was also noted for the water content measurements
- Ground water levels up to 2.3 m asl have been measured in MB21 during the period – this is above the lowest water content sensor at 2.0 m asl, but beneath the other sensors.
- The deepest ground water levels after a long dry period have been 0.7 m asl

Previous measurements of water content in the testpit for the period 2006-2010 are presented and discussed in Matthiesen (2010), and the data are repeated in Figure 5. The overall tendency is a slow decrease in water content in the four soil layers monitored over the four year period. It cannot be ruled out that there may be some drift of the equipment (as it hasn't been calibrated for 4 years) but it is difficult to prove as several of the sensors have stopped working.

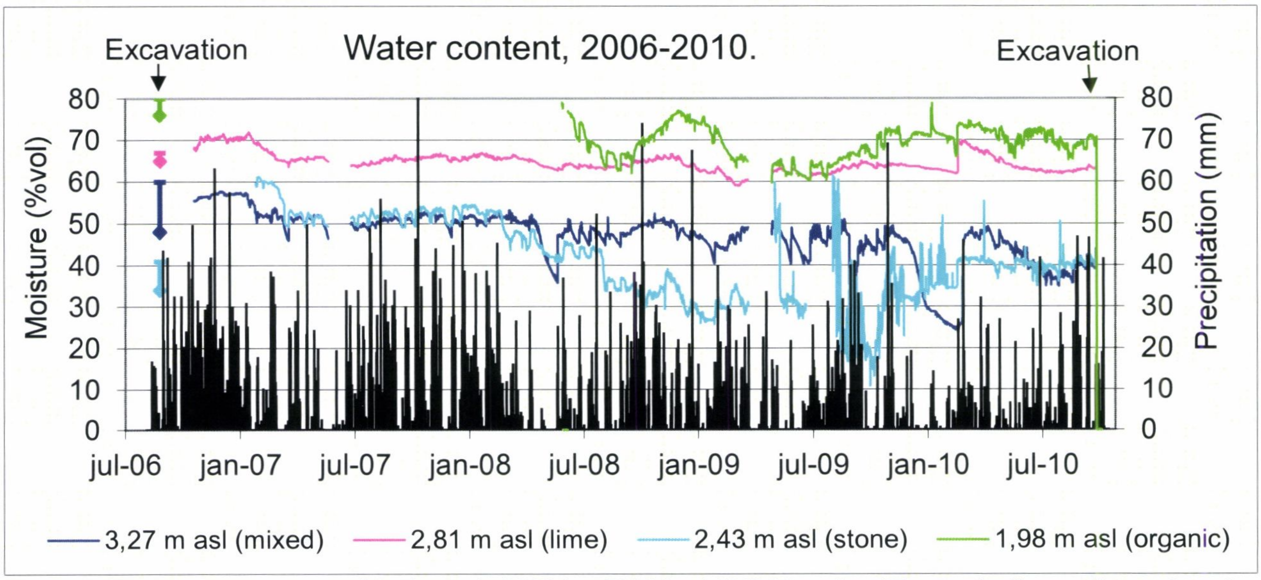


Figure 5: Water content measured in the period 2006 to 2010 by 4 SM200 probes. The results from soil samples taken during the excavation in September 2006 are shown to the left (soil porosity shown as horizontal lines, water content during the excavation shown as diamonds). The daily precipitation values (black columns) are taken from www.met.no for the Florida weather station in Bergen. The output from the sensor at 1.98 m asl (organic) was "over range" for the first two years, indicating a water content of 80% vol or higher.

Ground water levels measured in MB7 and MB21 in the same period are shown for comparison in Figure 6. It is remarkable, that the ground water level at MB7 during dry periods has been significantly deeper than in 2011 – reaching levels below 0.5 m asl every summer, and a level of only 0.2 m asl during winter 2010.

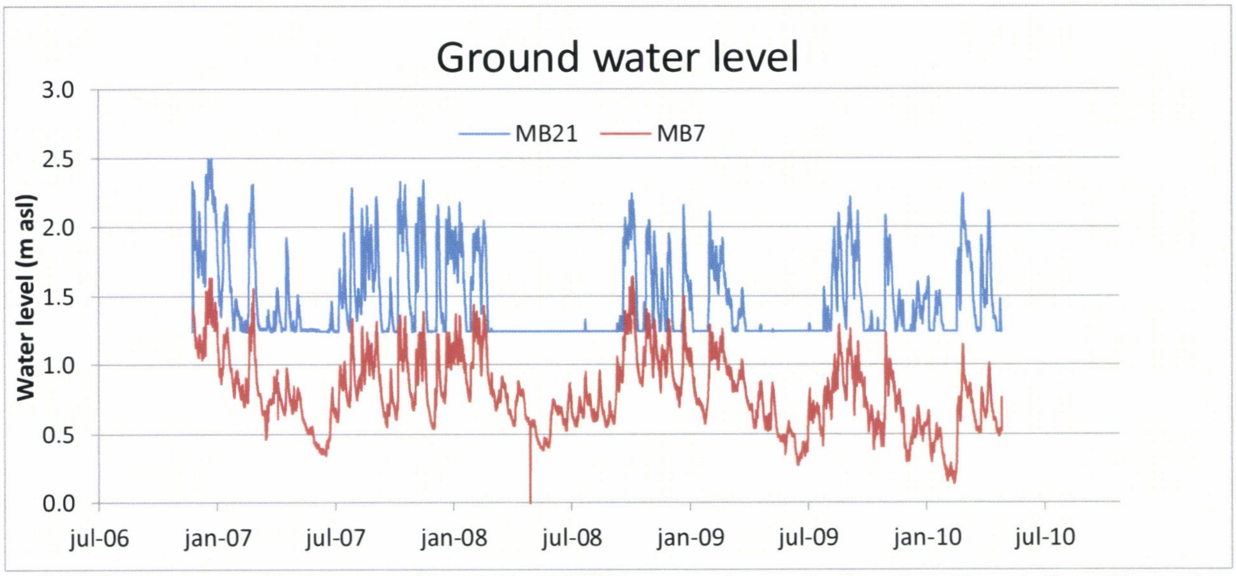


Figure 6: Ground water level measured in MB7 and MB21 next to the testpit. Data from Hans de Beer, Norwegian Geological Survey. The water level logger in MB21 was hanging too high in the dipwell, and in periods with a low ground water level the logger was above the water giving a constant reading (seen as horizontal lines)

Oxygen concentration

Oxygen concentrations measured in the different soil layers are shown in Figure 7.

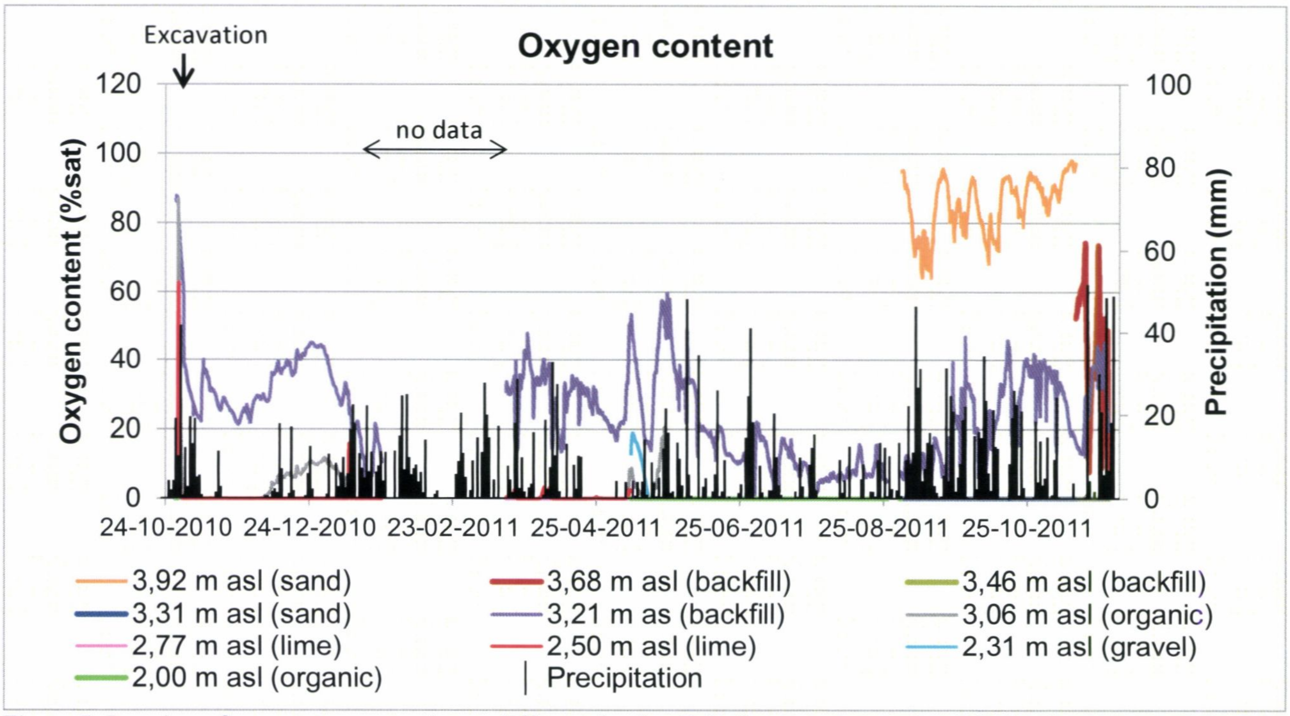


Figure 7: Logging of oxygen concentration at different depths. Only four sensors are logged at a given time, as described in Table 2.

The results for each individual soil layer and the correlation between oxygen and precipitation are discussed in detail below. However, as a general picture it is observed for the period October 2010 to November 2011 that:

- There is an initial phase just after the installation where oxygen contents are high, probably because of disturbance of the system by backfilling the excavation pit.
- There is a significant temporal variation in the oxygen concentrations, except for a few sensors that indicate permanent anoxic conditions.

Instead of showing time series, the oxygen data may also be presented as depth profiles, where the oxygen concentration at different depths is presented to make the depth distribution more clear. Figure 8 (left) gives examples of oxygen concentrations measured after the testpit was backfilled, showing both complete profiles measured manually during visits to Bergen, as well as the concentration ranges measured during the period that that sensor was connected to the logger. In previous reports oxygen measurements made in the open testpit in 2006 and 2010 have been presented (Matthiesen 2007; Matthiesen and Hollesen 2011) and the results are repeated in Figure 8 (middle). The shape of the oxygen profiles before and after closing the testpit is similar, but it cannot be excluded that some of the measurements made during excavations are biased as the oxygen can enter the soil not only from the soil surface, but also through the open testpit.

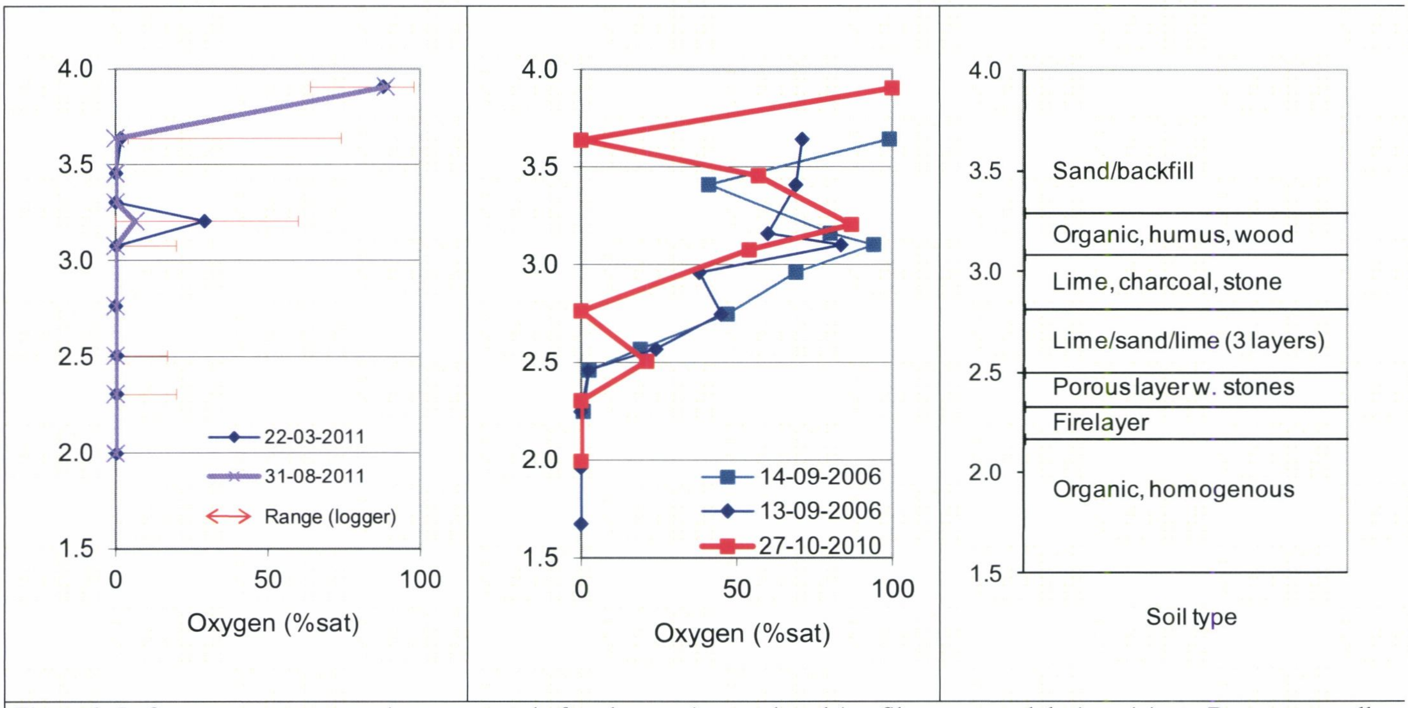


Figure 8: Left – oxygen concentrations measured after the testpit was closed (profiles measured during visits to Bergen, as well as range measured in the period the sensor was connected to the logger). Middle - results from measurement of oxygen in open testpits. Right – brief description of soil strata

Temperature

Measurements of soil and air temperature are presented in Figure 9. At this stage the temperatures are mainly used for calculating the exact oxygen concentrations as the calibration is strongly dependent on temperature. However, the data may also be used in a future discussion of heat flow and temperature effects on decay in cultural layers.

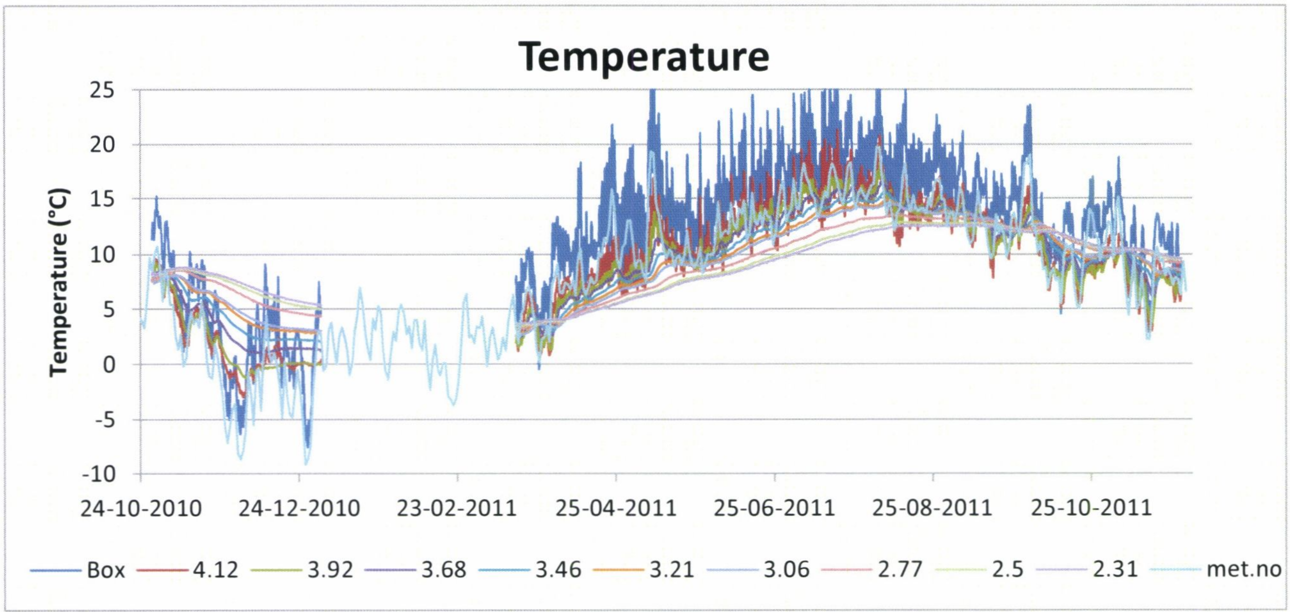


Figure 9: Temperature measurements in the different soil layers, and air temperature measured in the logger box. For comparison are given air temperatures from www.met.no, station Bergen, Florida.

Decay of organic material

The reactivity of wet soil from four soil layers from the testpit has been studied at different temperatures in the laboratory (Table 3). The deepest soil layer (at 2.1 m asl) is by far the most reactive. All measurements have been made at full oxygen saturation, measuring how fast the sample consumes oxygen in a closed vial.

Layer	5 °C	10 °C	15 °C	20 °C
3.3 m asl (layer 4/6)*			< 0.002	
3.1 m asl (layer 8)	0.001	0.004	0.004	0.007
2.7 m asl (layer 9)	0.001	0.003	0.003	0.006
2.1 m asl (layer 14)	0.019	0.021	0.030	0.052

Table 3: Reactivity of soil samples from different layers. The reactivity is measured as the oxygen consumption at a given temperature and water content, as described in Hollesen and Matthiesen (2011b). Results are given as mg oxygen consumed per g wet soil per day. *only measured at 15° C, and using a technique with a slightly higher detection limit, as described in (Hollesen and Matthiesen 2011a).

The decay of modern pine samples has been investigated in situ (Table 4). The samples were placed in the soil for 4 years from 2006 to 2010, after which they were retrieved and analysed in the laboratory. The height of the samples has been estimated as described in Matthiesen and Hollesen (2011).

Estimated height (m asl)	Soil layer	Density (g/cm^3)	White rot	Soft rot	Erosion bacteria	Other comments
3,27	Mixed	0,40/0,39	-	X	**X**	Light coloured
3,04	Organic	0,41/0,41	-	**X**	X	Slightly darkened
2,81	Lime	0,48/0,43	-	-	X	Light coloured
2,43	Stone	0,41/0,40	??	X	X	Darkened
1,98	Organic	0,45/0,46	-	-	X	Light coloured

Table 4: Analysis of modern pine samples after 4 years in the ground. **X:** massive attack ; X: identified; ?: possibly identified; -: not found.

Discussion

Several questions were listed in the introduction, all being relevant for the mitigation strategy used on Bryggen. It is not possible to answer all the questions yet, but they may be used to structure the discussion:

Correlation between precipitation, water content and oxygen

Not surprisingly, there is a clear connection between the precipitation, the ground water level, and the water content of the different soil layers, as shown in Figure 3 and 4: For some layers precipitation results in an immediate increase in the water content (e.g. at 2.37 and 3.09 m asl) whereas in other layers the response is slower (e.g. at 2.77 m asl). Such differences may be explained by differences in the soil properties (coarse grained soil material shows a faster response than fine grained material) as described in more detail below. The ground water level measured in MB21 next to the testpit is no higher than 2.3 m asl and only seldom exceeds 2.0 m asl (Figure 4). This indicates that only the deepest water content sensor at 2.0 m asl is occasionally beneath the ground water level, whereas the sensors higher up in the soil profile are not.

When it comes to long term changes it was noted in Matthiesen (2010) that there is a tendency of decreasing water content in the different soil layers in the period 2006-2010 (Figure 5), but no explanation was given. The decrease in water content could be a long term effect of the drainage in the area, slowly drying out the different soil layers. However, there could also be an effect from natural variations in the precipitation: Table 5 shows the yearly amount of rain in Bergen, which has decreased in the period 2007-2010 (from www.met.no). For comparison is shown the yearly average in water content measured in four different soil layers, as well as the ground water level measured in MB7, which have also decreased during the same period. 2011 was more wet than 2010, with 2685 mm precipitation. The average ground water level in MB7 (January to end of September 2011) was 1.18 m asl, i.e. significantly higher than during the later years.

	Precipitation	Water content, yearly average (%vol)				Ground water level (m asl)
	mm/year	3.27 m asl	2.81 m asl	2.43 m asl	1.98 m asl	MB7
2007	3025	52	66	*53*	*>80*	0.85
2008	2513	49	65	43	*70*	0.86
2009	2093	46	63	30	67	0.76
2010	1626	*39*	*64*	*39*	*71*	*0.56*

Table 5: Yearly precipitation for the period 2007-2010 measured at Florida weather station in Bergen. For comparison are shown the average water contents measured in different soil layers in the same period as well as the ground water level measured in MB5. Numbers are shown in italics if there is not data for the full year.

Only a minor part of the precipitation infiltrates into the ground, but at this point it is still uncertain how much. The monitoring data presented here might be used to find a more exact correlation between precipitation and water content of the soil, and make a local water budget.

The combination of water content (Figure 3) and oxygen concentration (Figure 7) makes it possible to study the connection between water and oxygen in the soil, and for instance evaluate to which extent oxygen dissolved in rainwater is transported down into the soil. This is easier if the data are presented in the same graph, and examples of direct comparison between water content and oxygen concentration are given in Figure 10 and 11:

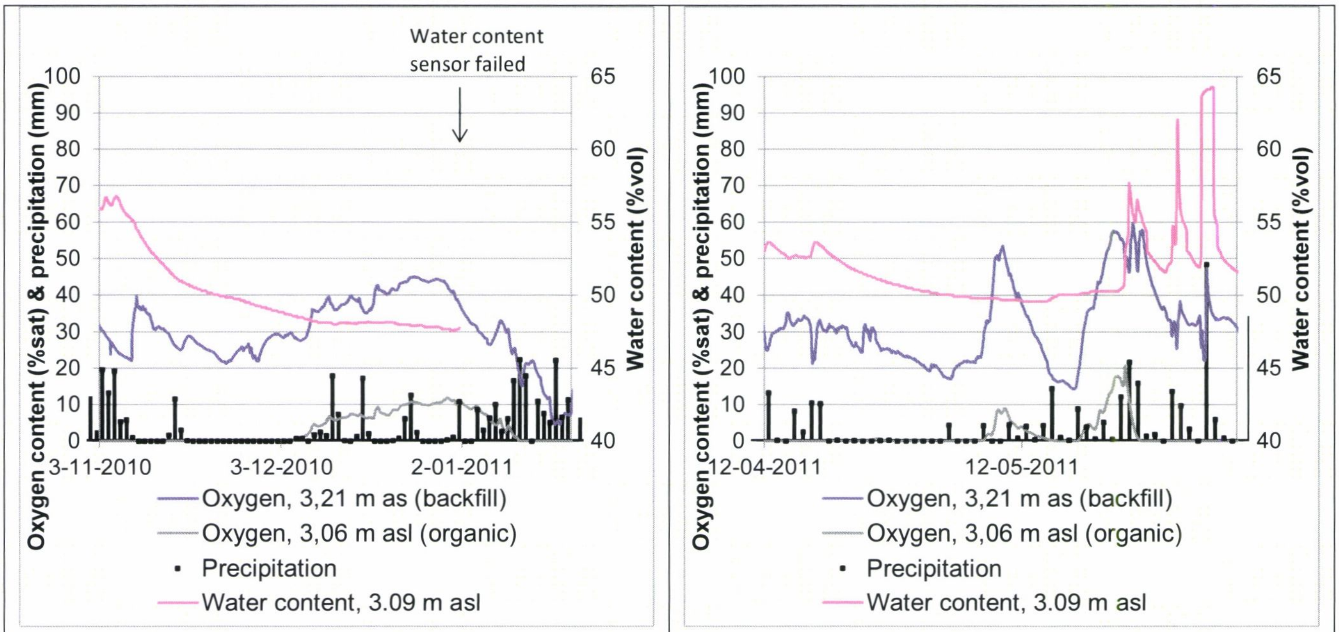


Figure 10: Examples of the connection between water content (measured at 3.09 m asl) and oxygen concentration (measured at the two closest sensors, at 3.06 and 3.21 m asl) during and after two dry periods

Figure 10 shows the effect of two dry periods from 17/11-11/12 2010 and 19/4-2/5 2011. In both instances the water content in the soil (here measured at 3.09 m asl) slowly decreases. When the water content has dropped to a level of approximately 48-50%, free oxygen appears at the sensor at 3.06 m asl and the oxygen concentration increases at 3.21 m asl. This is interpreted as a change in oxygen supply: when the soil becomes sufficiently dry, the diffusion of oxygen into the soil is faster than the consumption, and free oxygen is measured.

When it starts raining it takes some time before the water content increases at 3.09 m asl and the oxygen disappears. In Figure 10 (right) is seen how the water content increases slightly on the 16th of May, giving a temporary decrease in oxygen content at both 3.21 and 3.06 m asl. The water content increases more significantly on the 24th of May after which the conditions at 3.06 m asl return to more permanent anoxic. The picture in December and January (Figure 10 left) is similar, but due to freezing temperatures during most of December some of the precipitation fell as snow, which does not influence the water content in the soil before the snow thaws. January was warmer, and very wet, and the oxygen concentrations in the soil decreases. Unfortunately the water content sensor stopped working on the 1st of January, so we don't see the increased water content in the figure to the left.

In relation to infiltration of rain water it has been discussed to which extent oxygen dissolved in the rain actually reaches the cultural layers. For instance in the dipwell MB5 on Bryggen it has been demonstrated that the oxygen concentration in the saturated zone increases abruptly during heavy rain, indicating that the water flow around MB5 is so fast that the dissolved oxygen isn't used up during its transport through the soil (Matthiesen 2005). As for the testpit discussed in this report, Figure 11 shows some examples of oxygen measurements in the unsaturated zone in periods with heavy rain. To the left is demonstrated how the water content at 3.09 m asl increases abruptly during heavy rain, and the oxygen concentration at 3.21 m asl drops at the same time. This is most notably in the period 29/6-1/7 2011 where there was 100 mm precipitation in 4 days - here the conditions became completely anoxic around the oxygen sensor. As for the conditions in the uppermost soil layers, Figure 11 (right) shows the results from a water content sensor and oxygen sensor at 3.92 m asl just beneath the cobblestone as well as an oxygen sensor at 3.68 m asl – also here the oxygen concentration decreases during periods with heavy rain. This indicates that normally the netto effect of rain is a decrease in oxygen concentration in the unsaturated zone (in other words: the increase in soil moisture and decrease in oxygen diffusion rate has a greater effect on the oxygen supply, than the small amount of oxygen dissolved in the rain). This observation is of course important when discussing mitigation strategies such as re-infiltration.

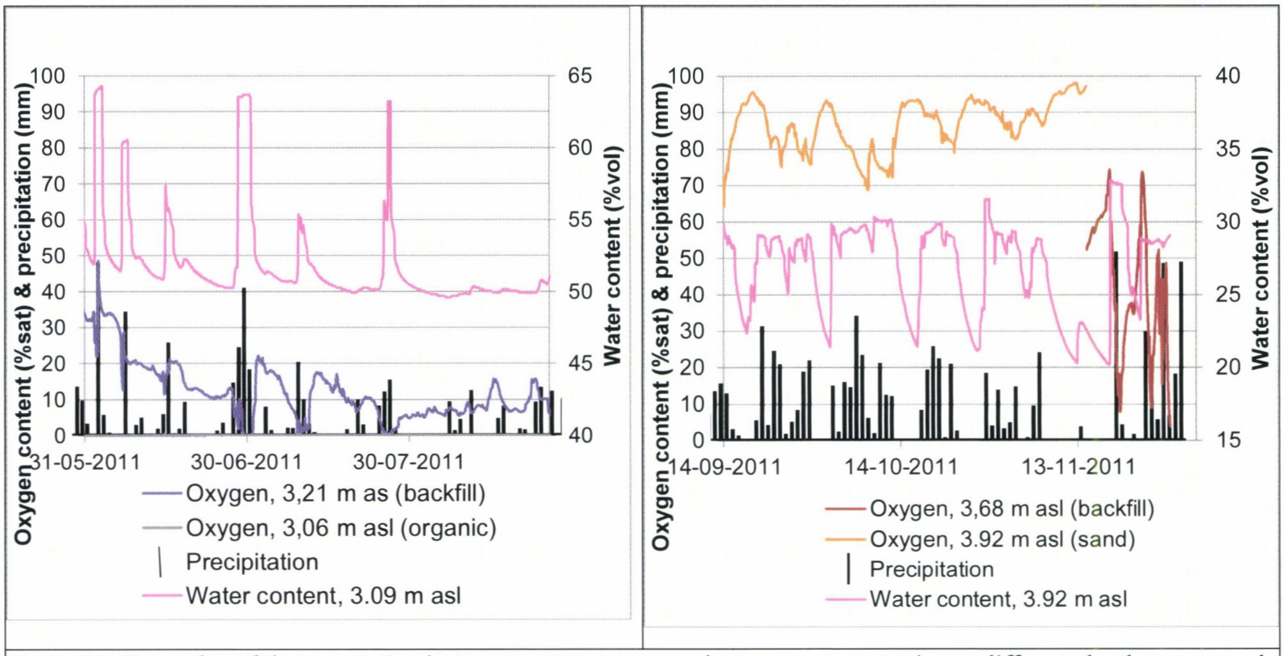


Figure 11: Examples of the connection between water content and oxygen concentration at different depths, measured during two wet periods

A more detailed analysis of oxygen dynamics during and after rain fall would require a better time resolution of the precipitation data – at this stage we only have daily values.

Where and when does the decay take place?

Oxygen sensors have been installed at 10 different depths (Table 1), and it is relevant to discuss the measurements for each individual layer, in order to understand the transport and consumption down through the soil column. There are only limited data available at this point, so the discussion and conclusions can only be preliminary.

3.92 m asl – in a sand layer just beneath the cobblestone. Here the oxygen concentration has been monitored from 1/9/2011 – 14/11 2011. The results show oxygen concentrations between 64 and 98% saturation. In the same period temperature varied between 6-15 °C and the water content between 20-31% vol. The water content has been monitored in the periods 29/10-31/12 2010, 17/3-19/5 2011 and 1/9-1/10 2011; it is relatively dynamic, varying between 18-33 %, and with a quick response to precipitation. During winter it seemingly drops to very low levels, but this is due to water freezing. For comparison the porosity has been measured to 39%, so the soil is not waterlogged at any time, and the air filled volume varies between 6-21%. Based on these data it may be assumed that oxygen is present in high concentrations all year round. The reactivity of the soil has not been measured, but based on a low organic content (0% loss on ignition) it is assumed to be very low.

3.68 m asl – in backfill material. Here the oxygen concentration has been monitored from 14/11 – 28/11 2011. The results show highly variable oxygen concentrations between 4 and 74% saturation, with a distinct (negative) correlation to the precipitation (Figure 11). In the same period the temperature varied between 6-8 °C. The water content in the layer has been monitored in the periods 29/10 – 31/12 2010 and 17/3-19/5 2011, after which the sensor stopped working. In this period the water content varied between 34-41%, with some response to precipitation, but not as fast or distinct as the sensor at 3.92 m asl. The porosity of the soil layer couldn't be measured.

3.46 m asl – in backfill material. Here the oxygen concentration has been monitored from 14/11 – 28/11 2011, and during that period no oxygen was measured at any time. The monitoring period was quite wet with 170 mm rain during the 2 weeks, which may contribute to the anoxic conditions. For the water content – see description for 3.68 m asl.

3.31 m asl – in a sand layer (Layer 6 – Dutch sand). Here the oxygen concentration has been monitored in the period 1/9 – 14/11 2011, and during that period no oxygen was measured at any time. The period was very wet with 360 mm rain in a month, which may contribute to the anoxic conditions.

The water content was only measured in the period 29/10 – 31/12 2010, which was right after the excavation pit was backfilled with wet soil. During that period the water content slowly decreased from 48 to 40%, with a very slow response to precipitation. The porosity of the soil was measured to 45%, i.e. the soil layer was close to saturated during the period, with an air content lower than 5% vol. The organic content of the layer is low, with a loss on ignition around 2%, so there is probably not much decay taking place in this soil layer.

3.21 m asl – in backfill material. Here the oxygen concentration has been monitored continuously in the period 9/10 2010 – 23/1 2011 and 17/3- 28/11 2011. The oxygen concentration is highly variable (values between 60% and 0% saturation). In general there is a negative correlation to the precipitation, and completely anoxic conditions are only found on days with heavy rainfall (for instance 29/6-1/7 2011 where there was 100 mm precipitation in 4 days – Figure 11, left). There are however also some dry periods that show decreasing oxygen concentrations (for instance 8/11-18/11 2011) which haven't been fully understood yet. 100% oxygen saturation is not reached at any point during the monitoring. The water content has not been monitored in exactly the same soil layer as the oxygen, but in the period 2006-2010 it was monitored in a mixed soil layer at 3.27 m asl. This showed a long dry period during winter and spring 2010, where the water content decreased to 25 % vol (compared to a soil porosity of 60%) and where the oxygen concentration might have been higher than the 60% saturation measured in 2011. Analysis of modern wood samples from this depth showed decay by soft rot (Table 4) which corresponds well with the presence of oxygen. The reactivity of the soil has not been measured specifically for the backfill material, but samples from the upper soil layers (layer 4-6) showed a quite low oxygen consumption (< 0.002 mg O_2/g/day at 15 °C which is close to the detection limit of the method – Table 3). The permanent presence of oxygen indicates that decay can take place all year round.

3.06 m asl – in an organic-rich sandy layer with timber (layer 8). Here the oxygen concentration has been monitored continuously in the period 9/10 2010 – 23/1 2011 and 17/3- 28/11 2011. During this period the conditions have been anoxic most of the time, but there are some events (6/12/2010-11/1/2011 and 6/5-25/5 2011) where oxygen is present in a concentration of up to 20% saturation. The water content has been monitored in the same period, showing values between 48-63%. On several occasions with heavy rainfall the water content is as high as the soil porosity (62%), which means that the soil at 3.06 m asl is temporarily water saturated, despite the fact that the ground water level measured in MB21 is seldom higher than 2.0 m asl (Figure 4). The presence of oxygen correlates with long dry periods when the water contents decreases to 48-50% vol (Figure 10), compared to a soil porosity of 62% - i.e. oxygen appears when the "air content" of the soil is higher than 12-14%. The occasional presence of oxygen fits well with the occurrence of soft rot in modern wood samples placed in the soil in the period 2006-2010 (Table 4). The loss on ignition of the soil is 20 % on average so there is a large amount of organic material that may be oxidized. As for the reactivity of the soil layer, its oxygen consumption was measured to vary between 0.001 and 0.004 mg O_2/g/day at 5 and 15 °C respectively, and the soil temperature at this depth varies between 3 and 15 °C during the monitoring period. Overall, the occasional presence of oxygen and the reactivity of the soil material indicate that decay takes place in this soil layer during dry periods.

2.77 m asl – in a compact lime/sand layer (layer 9/10). Here the oxygen concentration has been monitored in the period 9/10 2010 – 23/1 2011 and 17/3- 9/5 2011. During the whole period there have been anoxic conditions, even during the long dry period in December 2010. The water content has been monitored in the same period showing very stable results between 66 and 68%, compared to a porosity of approximately 68% (i.e. close to waterlogged conditions). Only on a few instances with heavy rainfall (for instance the 6/4-11/4 2011) the water content increases for a short while to fully water logged conditions (Figure 3) which is the same periods where the water level measured in MB21 exceeds 2.0 m asl (Figure 4). The water content has been monitored in the lime layer in the period 2006-2010, showing quite stable conditions with variations between 60-70% vol. It cannot be excluded that some oxygen may appear at the lowest water contents, but this remains to be demonstrated by further monitoring. Permanent anoxic conditions are in correspondence with the fact that no fungal attack was seen for the wood samples placed in the lime layer. The loss on ignition of the soil is 6% on average so there is some organic material that may be oxidized. As for the reactivity of the material, its oxygen consumption was measured to vary between 0.001 and 0.003 mg O_2/g/day at 5 and 15 °C, respectively. However, as there is no oxygen present in the soil it is estimated that only very limited decay takes place here.

2.50 m asl – in a fine grained lime layer (layer 11). Here the oxygen concentration has been monitored in the period 9/10 2010 – 23/1 2011 and 17/3- 9/5 2011. During most of the period there have been anoxic conditions, but occasionally oxygen is present for a few days (most notably on the 9/1-12/1 2011 but oxygen also appears in low concentrations on the 17/3-21/3, 1/4-5/4 and 7-9/5 2011). The water content has been monitored in the lime layer just above (at 2.77 m asl) with very stable results as described above. The explanation for the brief occurrences of oxygen in the lime layer is not clear yet, but it may be connected to occurrence of oxygen in the porous gravel layer just beneath.

As for the reactivity of the material, its oxygen consumption of the lime layer was measured to vary between 0.001 to 0.003 mg O_2/g/day at 5 and 15 °C, respectively. However, as oxygen is only very infrequently present in the soil it is estimated that only limited decay takes place here.

2.31 m asl – in a layer of gravel and coarse sand. Here the oxygen concentration has been monitored from 9/5-26/8 2011. Oxygen was only present in the very beginning (9/5 – 16/5 2011) reaching concentrations up to 20% saturation; this was at the end of a long dry period. The water content was measured during the whole period, fluctuating between 32 and 46%. The porosity of the soil was measured in the laboratory to 43%, but in periods with heavy rainfall the water content shows quite stable values up to 46%, which is probably the in situ porosity indicating that the soil is water saturated. In the period 9/5 – 16/5 2011 (where oxygen was present) the water content was 32%, and the air content thus ca. 14% vol. A similar low water content was measured during December 2010 (Figure 3) and the long term monitoring (Figure 5) showed that the water content was around 30% or lower during all of 2009. It is assumed that oxygen may have been present on these occasions as well. This fits well with the occurrence of soft rot in modern wood samples placed in the soil in the period 2006-2010 (Table 4). As for the reactivity of the soil, it has not been measured for this layer of gravel and coarse sand, where the organic content is only 3%. The soil layer just beneath is on the other hand very organic, and it cannot be excluded that oxygen from the gravel layer reacts with organic material from this deeper layer.

2.0 m asl – in a highly organic layer with timber. The oxygen concentration has been monitored from 9/5/11 – 26/8/11, and at no point during this period free oxygen has been measured. The water content in the layer was very stable, decreasing slowly from 68 to 66% during the period (Figure 3). A longer time series (Figure 5) indicated a slow drying out of this soil layer, as the water content decreased from >80% to 70% in the period 2006-2010. As the water content has been higher earlier on, it is estimated that the anoxic conditions found today have been prevailing during the whole period – this is corroborated by the fact that no fungal attack was seen for the wood samples placed in this organic soil layer. The porosity measured for the soil layer is 80%, so the air content of the soil has increased from 0% to 14% over the last 5 years. The organic content of the soil is 41% so there is a lot of material that may potentially be oxidized. As for the reactivity of the material, its oxygen consumption at in situ temperatures (which varies between 7 and 12 °C) was measured to 0.02-0.03 mg O_2/g/day, which is 5 to 10 times higher than in the soil layers above. The anoxic conditions observed may be explained by a relatively slow oxygen transport through the lime layers above and the wet organic soil itself, combined with the high reactivity quickly consuming any oxygen that reaches the layer. However, the decreasing water content is a bit worrying as it may over time give an increased oxygen transport to the layer and thus an increased decay at the top of the layer, which does not necessarily reveal itself by any free oxygen at the depth of the oxygen sensor.

So in order to sum up the information at this stage, the data indicates that oxygen is normally present in the upper coarse soil layers such as the sand layer at 3.92 m asl and the backfill layers at 3.68 and 3.21 m asl; it appears after dry periods in the layer at 3.06 m asl and 2.31 m asl; and it appears rarely (or never) in the deeper fine grained layers at 2.77 m asl, 2.50 m asl and 2.00 m asl. However, these conclusions are based on very short monitoring periods and the trends need to be validated by monitoring the oxygen concentration at different depths for longer time periods and under extreme conditions such as long dry periods – most of the oxygen data are from 2011, and for instance 2010 was significantly more dry.

For the uppermost soil layers, the organic content is low and not very reactive. Thus the combination of reactive organic material and (occasional) occurrence of oxygen is mainly found around the oxygen sensors at 3.06 and 3.21 m asl, which means that decay of organic material is most likely taking place here. The conditions within the deepest soil layer around 2.0 m asl is a "dark horse"- here the soil material is very reactive, and if oxygen occasionally reaches this soil layer, it will probably be used up before it reaches the oxygen sensor placed within the soil layer. Further monitoring is necessary (at all depths especially during dry periods) to estimate exactly where and when the decay takes place, and if the decay caused by oxygen is sufficient to explain the observed settling in the area.

How wet is wet enough?

It is too early to say "how wet is wet enough" to retain anoxic conditions and reduce the decay at the site: Permanent waterlogged conditions at all depths would obviously help but is not a realistic scenario, and we still don't know exactly how much decay takes place during long dry periods compared to the rest of the year. However, for a few of the soil layers we have oxygen and water content measurements during both oxic and anoxic conditions, and thus for these layers we have an idea of which water content is necessary to keep the oxygen away: At 3.06 m asl oxygen appears when the water content decreases below 50% vol, corresponding to an air content > 12% (calculated as porosity minus water content). At 2.31 m asl oxygen appears when the water content is below 32% vol, which corresponds to an air content > 11%. At 2.77 m asl there are permanent anoxic conditions, and the air content has not been higher than 5% vol during the monitoring period. This could indicate that oxygen is mainly present in these upper soil layers when the air filled volume (i.e. the porosity minus the water content) exceeds approximately 10% vol. The influence from the air filled volume on the oxygen diffusion down through the soil in the testpit has already been described in Matthiesen et al. (2008), based on the theory and equations given by Jin and Juri (1996).

It will probably not be possible to find one specific water or air content where all soil layers are anoxic, as the oxygen concentration not only depends on the diffusion, but also on the consumption of oxygen. For instance in the very top, at 3.92 m asl, the oxygen consumption of the sand is very low and oxygen is found even during the wet September 2011, where the water content reaches 31% and the air content is only 8% vol. On the other hand, at the deepest soil layer, at 2 m asl, the reactivity of the organic soil is quite high, and no oxygen has been measured during the monitoring period even though the water content has dropped to 66%, corresponding to an air content of 14% - here it cannot be excluded that some oxygen actually reaches the deep layer for instance during dry seasons, but is consumed before it reaches the oxygen sensor.

Obviously, this is all quite theoretical and needs to be validated by further monitoring at Bryggen and at other sites, and it must also be emphasized that porosity measurements and the absolute values for the water content are connected with some uncertainty. At this point we may only use "max 5-15% air" as a very rough rule of thumb of "how wet is wet enough" for the different soil layers.

The soil porosity is needed to calculate the amount of air in the soil, but it is not always possible to get good measurements of the porosity, especially if the monitoring equipment is installed by drilling. However, in this study it has been observed that the "peaks" in water content, seen during heavy rainfall, may in some cases be used to estimate the in situ porosity of the soil around the water content sensor (Figure 3).

Is oxygen the main cause of decay?

This monitoring project and report has a strong emphasis on oxygen, as it is fairly reactive and for instance wood decaying fungi depend on oxygen for their survival. It is the only oxidant that is supplied through the gas phase, and the only oxidant where the supply is increased directly through drainage and a lowered water table. For these reasons it is natural to focus on oxygen in the drained area on Bryggen, where decay and settling of the soil surface is faster than in other areas on Bryggen.

However, at this stage there is not enough data to quantify the yearly decay by oxygen down through the soil sequence, and thus not possible to verify if oxygen is actually the only important cause of decay or if other oxidants or mechanisms are in play. Other oxidants include mobile species such as nitrate and sulphate, and immobile species as iron oxides and manganese oxides. Nitrate and sulphate could be supplied and re-distributed by infiltrating water. The concentrations in rainwater are normally low (a few mg/L for each species, which is slightly lower than the concentration of oxygen dissolved in rain). However, due to the drainage in the area there may also

be a pool of sulphate in the soil, as sulphate is produced through the oxidation of for instance iron sulphides by oxygen. Work is ongoing to measure how reactive soil material from the testpit is towards nitrate and sulphate reduction (Hollesen and Matthiesen 2011a).

As for iron and manganese oxides, the most reactive oxides will normally have been reduced in the first centuries after burial in organic rich, water logged archaeological layers. However, after drainage fresh iron and manganese oxides – as well as sulphate - may be produced by reaction with oxygen. The concentrations of these species are not known for the testpit, but they may represent a pool of oxidation capacity that can postpone the positive effects from raising the ground water table. The measurements of redox potential at the testpit may shed some light on which processes are on going (Appendix 1).

Can we document the effect of different remediation actions?

On the 18th – 23rd of November 2010 a short term experiment was made with raising the drainage level by 25 cm at the hotel next to Bryggen. This was done during a very dry period, and caused the groundwater to raise in large parts of Bryggen (Hans de Beer, pers.com). However, looking at the water content in the unsaturated zone, all sensors (except the deepest at 2.0 m asl) showed decreasing water contents during the period. The experiment was made permanent on the 7th of September 2011, where the drainage level was increased by 45 cm. Again the ground water table rose (Hans de Beer, pers.com), and the water content sensors in the unsaturated zone higher up showed relatively high water contents in September (Figure 3). However, the high water contents could also be due to natural variations as September was a very wet month, and it is difficult to document what is the effect specifically from raising the drainage level - for instance the water content at 2.37 m asl rose to 44 %vol (saturated conditions) already on the 3rd of September (i.e. a few days before the drainage level was increased) and remained there for the rest of September. It will be necessary to look at the long term data over the coming years to see if the average water content increases and if the oxygen penetration decreases.

As for the effect of re-infiltration, the first tests haven't started yet. Again it may be difficult to document the exact effect on the short term, as there is a significant natural variation in the data. However, on the long term it should be possible to document longer periods with a high water content and shorter periods with low water content.

Conclusions and future work

In order to sum up:

- The installation of sensors and monitoring system has been successful, even if there were some problems with old water content sensors that were reused – they are now failing and should be replaced.
- Oxygen is mainly found in the upper 1 m of the soil profile, and occasionally in a coarse gravel layer deeper down, which corroborates the observations from the 2006 and 2010 excavations, and in situ decay studies with modern wood samples.
- There is a clear connection between the precipitation, the water content and the oxygen concentration: During long dry periods, the water content of the soil layers decreases, and oxygen penetrates deeper into the soil, and when it rains the water content of the soil increases and the oxygen concentration decreases.
- Oxygen dissolved in rainwater does not have any significant impact on the preservation conditions in the unsaturated zone at this site - even during heavy rain the oxygen content of the soil decreases rather than increases
- As first rough estimate free oxygen appears in a soil layer when the air content (i.e. the porosity minus the water content) exceeds approximately 5-15% vol, but the estimate needs to be further validated with longer monitoring periods and in other soil types
- First data indicate that layers at 3-3.5 m asl are most prone to decay. There are a few long dry periods during the year where oxygen penetrates deeper into the soil, however it is too early to say if decay during these dry periods is more important than during the rest of the year.
- The monitoring period (October 2010 to September 2011) has not been especially dry, so the oxygen penetration and decay may reach deeper layers during dry years – for instance in 2009 and 2010 the ground water level in MB7 was significantly lower than during the period where oxygen has been monitored

It is recommended to:

- Upgrade the 4 channel oxygen meter to a 10 channel, which will allow simultaneous monitoring on all 10 sensors
- Install new water content sensors (Profile Probe) in the upper soil layers, in order to replace sensors that have failed
- Evaluate of the effect of different mitigation actions, such as raising the drainage level at the hotel site, re-infiltration, and/or sealing the sheet piling

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Appendix 1.

Measurements of redox potential in the soil next to the excavation pit.

Installation of the redox sensors is described by Vorenhout (2011). The first results were presented at a meeting in Copenhagen in December 2011. This was too late to have them fully integrated in the present report, but they are shown in this Appendix (with permission from Michel Vorenhout) along with a few initial remarks.

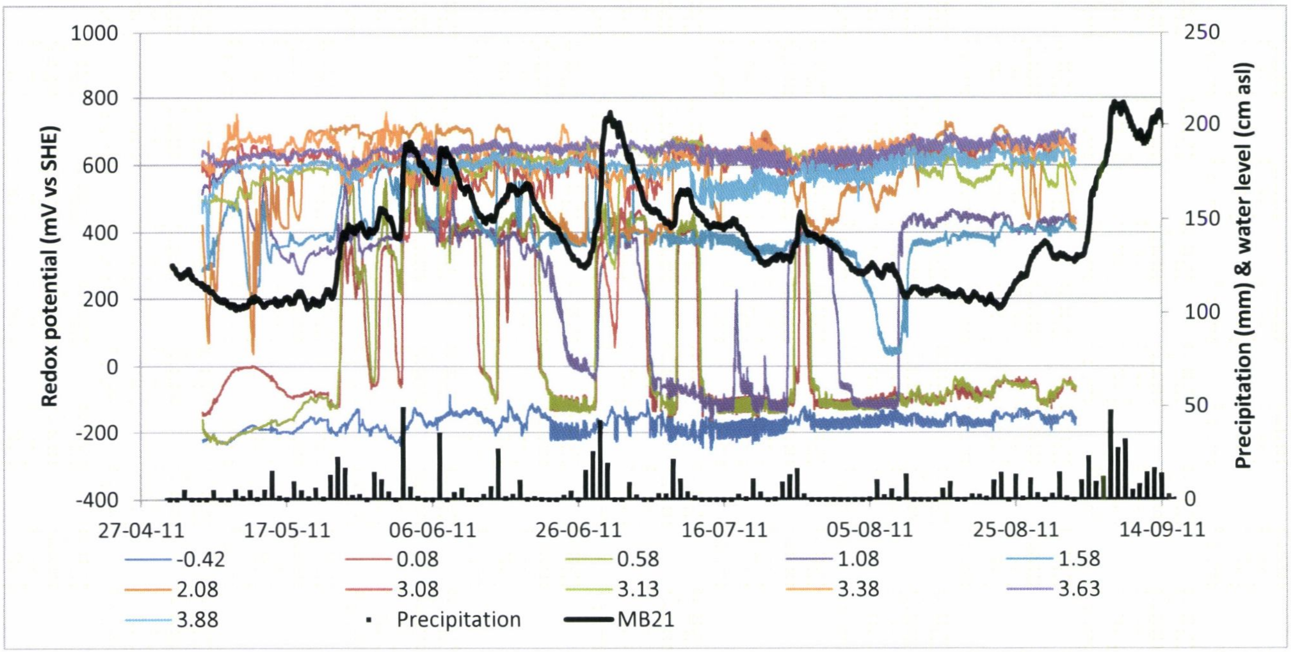

Figure 12: Initial results from measurement of redox potential at 11 depths in the soil – the name of the curves refer to the approximate depth in m asl. Also shown is the precipitation and water height as measured in MB21 between the testpit and the redox sensors.

The installation report gives the depth of the sensors relative to the soil surface. In order to find the depths in m above sea level, a reference level of 3.975 m asl has been used in Figure 12, corresponding to the soil surface around the sensors (height data received from Torben Nesse from Multiconsult, need to be validated by Vorenhout that this is the correct reference level). The sensors may be divided into 3 different groups according to their position relative to the groundwater level: Permanently above the groundwater level (Figure 13), permanently below the groundwater level (Figure 14) and in the fluctuating zone (Figure 15). During the monitoring period the groundwater level varied between 1.0 and 2.0 m asl in MB21 next to the redox sensors.

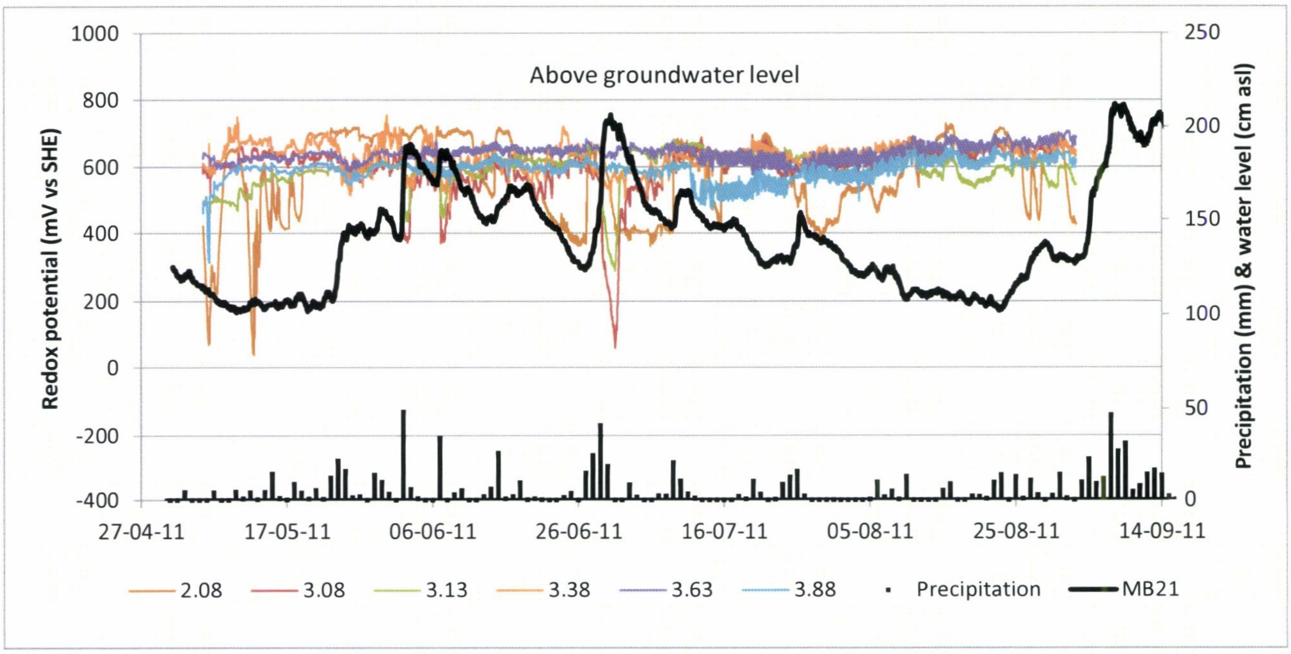

Figure 13:Initial results from redox sensors that have been permanently above the groundwater level measured in MB21.

The redox sensors above the groundwater level show potentials around 600 mV vs SHE most of the time corresponding to oxidizing conditions (Figure 13). The sensor at 2.08 m asl (closest to the groundwater) frequently drops to a level around 400 mV vs SHE which indicates more reducing conditions. After heavy rain, for instance 27th -31st of June, the potential of the sensors at 3.08 and 3.13 m asl also drop to a level of 400 mV vs SHE or lower. This is as expected: The conditions become more reducing when the water content in the unsaturated zone increases, and it is in good correspondence with results from the oxygen sensor at 3.21 m asl showing anoxic conditions in the period 28th of June – 1st of July (Figure 11, left). However, it is too early to say anything in general about the correspondence between oxygen and redox measurements, as for instance the next two periods where the oxygen sensor showed anoxic conditions (9.-11. July and 25.-27. July) are not so clearly reflected in the redox measurements.

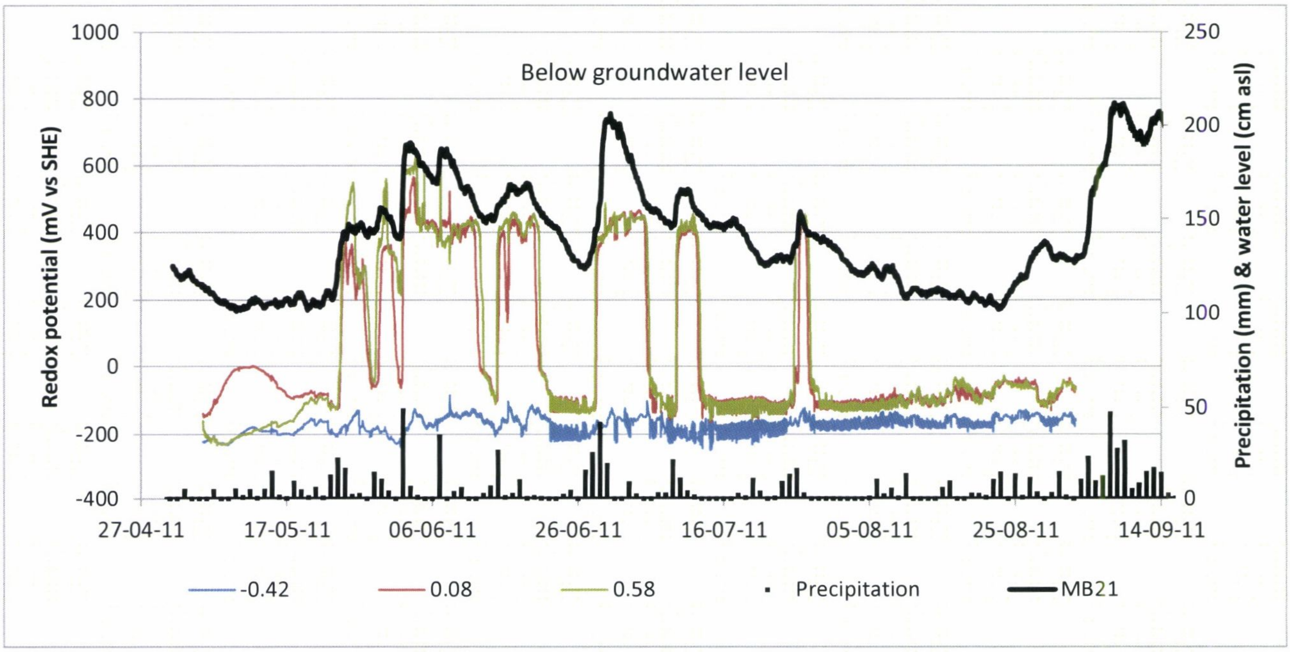

Figure 14: initial results from redox sensors that have been permanently below the groundwater level measured in MB21.

The redox sensors from the saturated zone beneath the groundwater level show the opposite behavior (Figure 14): Most of the time the sensors show potentials between -100 and -200 mV vs SHE corresponding to reducing conditions. However, after heavy rain when the groundwater level increases, there is a tendency that the redox potential increases abruptly up to approximately 400 mV vs SHE. This could be due to rainwater flushing through the saturated deposits, bringing water with a high redox potential down into the deeper deposits. However, it is necessary to validate if this is also the case in the bulk deposits or only around the redox sensors: The sensors were pressed down from the soil surface in a predrilled hole, and it is possible that this has created a preferential flow path through the deposits if the hole hasn't yet collapsed around the sensors. The deepest redox sensor at -0.42 m asl seems unaffected by the precipitation.

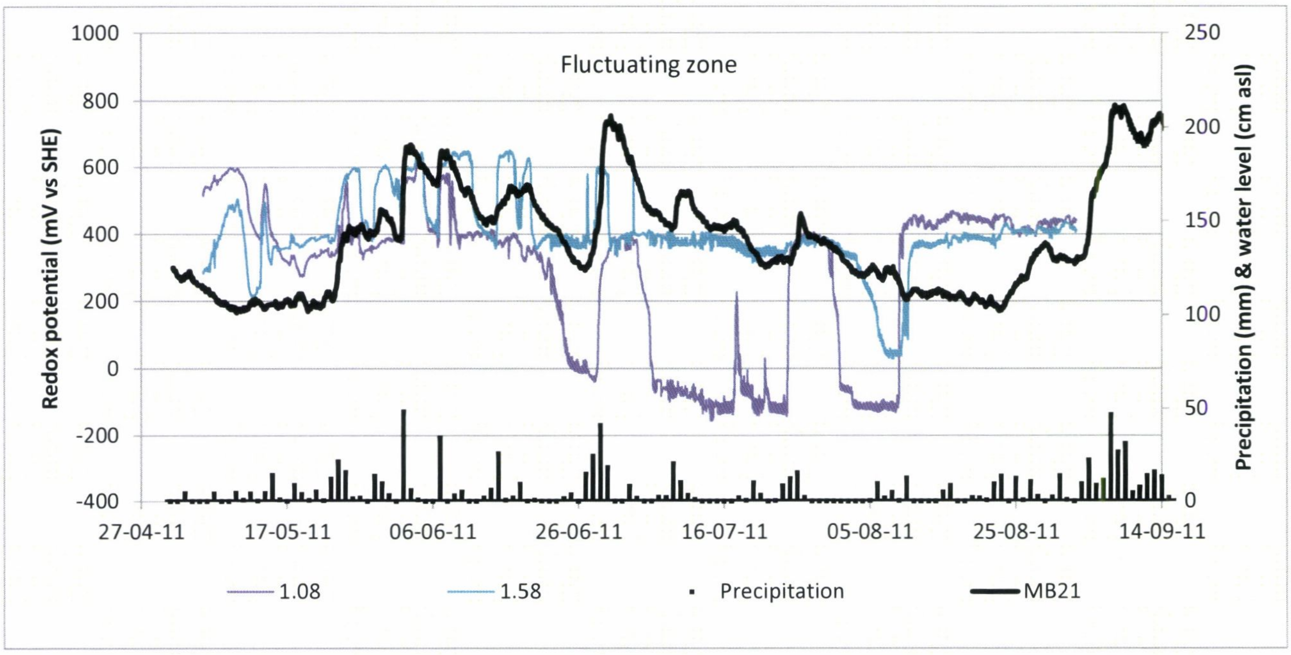

Figure 15: initial results from redox sensors that have placed in the fluctuating zone below the groundwater level measured in MB21.

The redox sensors from the fluctuating zone show a more complex pattern (Figure 15). For most of the period the redox values have been around 400 mV vs SHE, but with variations both up to 600 mV vs SHE and down to -100 mV vs SHE. There is a tendency that the redox potential increases when it rains and the groundwater level increases, but the tendency is not as clear as seen in Figure 14.