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Effects of infiltrating water  
into organic cultural layers





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*Department of Conservation*

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Effects of infiltrating water into organic cultural layers

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Summary:

The National Museum of Denmark has been asked by Riksantikvaren to make an evaluation of the effects of infiltrating water in order to improve preservation conditions at sites with organic cultural remains. A literature survey and direct contact to people working with in situ preservation gave a limited result and showed that there is little practical experience on the subject. Thus some experimental work has been included in this study to investigate some of the possible effects, before infiltration it applied full scale at archaeological sites. It has not been possible to cover all possible effects within the frames of the study, so focus has been on organic cultural deposits, and how their decay is effected by different water contents and water types.

Initial results from the laboratory and from ongoing monitoring at Bryggen in Bergen have validated the benefits of an increased water content of the soil, as a high water content reduces the oxygen supply and oxygen concentrations in the soil. Field data show that anoxic conditions occur when the air content of the soil (i.e. the porosity minus the water content) is below 5-15% vol, but these numbers need to be validated at other sites. An increased water content will normally decrease the decay rate, and only under extremely dry conditions will addition of water have the opposite effect. The effects of different types of water have been evaluated in terms of the reactivity of different oxidants dissolved in the water: The reactivity of dissolved oxygen and nitrate is high, but their concentration in most water is limited, and they are expected to have a limited effect in the unsaturated zone - field data from Bryggen thus shows that the oxygen dissolved in rain water normally is reduced before it reaches the cultural layers. The reactivity of dissolved sulphate is lower, but the concentration can be very high for instance in seawater - thus data from the laboratory study and from Bryggen have shown that the decay rate in sulphate rich deposits can be significantly higher than in sulphate free deposits. The effect from infiltration on soil temperature is expected to be limited, at least if rainwater is used in the infiltration.

Overall the study has validated the presumption that "any water is better than no water" and "stagnant water is better than flowing water", but it must be emphasized that the effect from infiltration on leaching or washing out of the deposits has not yet been evaluated. Some suggestions for further studies are given.

Signatures

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## **Introduction**

Drainage is one of the greatest threats to the preservation of organic archaeological layers: it increases the supply of oxygen into the soil considerably, which increases the decay rates of the organic material. There are numerous examples of archaeological layers being degraded due to drainage of previous water saturated soil layers, for instance at Star Carr in the UK (Boreham et al. 2011), and Åmosen in Denmark (Fischer et al. 2004; Matthiesen and Jensen 2005). The best known example in Norway is probably Bryggen in Bergen where the buildings and soil surface locally is settling by 6-8 mm/year due to the decay of organic archaeological layers (Jensen 2007).

One method to prevent the decay of the organic archaeological layers could be to infiltrate water into the layers and thereby increase the soil water content. There are a few scientific papers describing how active infiltration (re-watering) has been used as a method to prevent decay processes at archaeological locations: At the Rose Theater in London a leaky pipe system has been used to keep buried archaeological remains wet since 1989 (Corfield 2004), and at the Sweet Track in Somerset Levels, UK, a pumping system has been used since 1983 to retain a high groundwater level locally (Bunning et al. 2000). Direct contact to British and Dutch colleagues (Jim Williams and Jane Sidell from English Heritage, Ian Panter from York Archaeological Trust, Mike Corfield former chief scientist from English Heritage, and Hans Huisman from Netherlands Cultural Heritage Agency) didn't provide further examples of active infiltration at archaeological sites. At Ribe in Denmark leaky pipes were used in the rainwater sewer system in the 1990's and 2000's to increase infiltration into the cultural deposits (Ribe Amt and Ribe Kommune 2005) however, during the latest years this practice has been changed as there was a fear that the leaky pipes could serve as drains, rather than infiltration basins (Grønning 2011). Active infiltration using pumps has been used for instance in Copenhagen as a method to protect wooden foundation piles temporarily during construction projects (Stæhr and Lund 2003) or permanently (for instance at Eigtveds pakhuis at Christianshavn – Brendstrup 2010). A large European study on wooden piles (BacPoles) showed how softrot fungi attacked the piles if oxygen was available. Under anoxic conditions bacteria caused some wood decay – this is normally a much slower process than decay by fungi, but the study indicated that a high water movement through the soil could increase the bacterial decay rate (Huisman et al. 2008). This was corroborated in a microcosm study in the laboratory, showing that both the water flow and the content of nitrate and sulphate could have an effect on the decay rate – surprisingly the addition of nitrate, sulphate and glucose seemed to reduce the decay of wood and kapok, at least on a shorter time scale (Kretschmar et al. 2008).

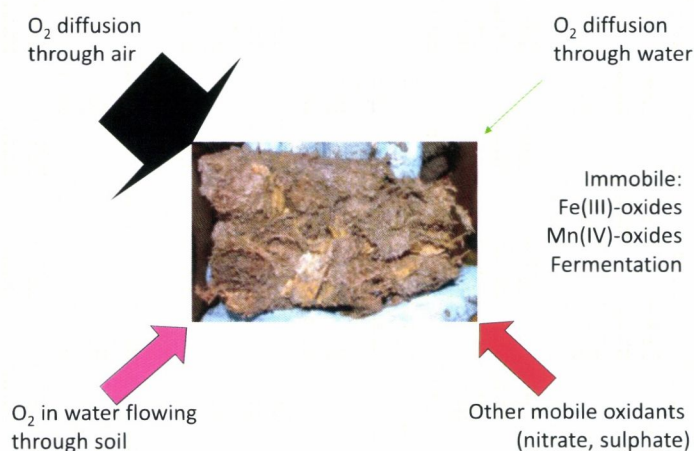
Riksantikvaren in Norway currently consider using active or passive infiltration to protect cultural layers at Bryggen and at several other locations in Norway. However, even though systems for active or passive infiltration are already used at a few archaeological sites in other countries, information on the exact effects of infiltration is very scarce and the risk of negative effects has not been investigated – or at least not published. Several questions need to be addressed before infiltration is used as a standard method to protect cultural deposits throughout Norway:

- 1) What is the minimum soil water content needed to limit the availability of oxygen – is it possible to establish a water content threshold for anoxic conditions?
- 2) Does the soil water content influence the decay in other ways – is the decay for instance limited in very dry soils?
- 3) What type of water should be used – does for instance the amount of dissolved oxygen, nitrate or sulphate influence decay rates?
- 4) Are there other effects that should be considered – for instance effects from infiltration on soil temperature or leaching of cultural layers?

The National Museum of Denmark has been contracted by Riksantikvaren to make a preliminary investigation of these questions. It was requested that material from Bryggen in Bergen should be used in the investigations.

## **Background**

The microbial decomposition of organic matter is the dominant process causing decay of organic archaeological layers. Soil organisms oxidize soil organic matter to inorganic forms primarily to extract energy for growth. Microbial decomposition rates depend strongly on the quality of the organic matter and on different environmental controls, of which water, oxygen availability, and temperature are among the most important (Schuur et al. 2008).



**Figure 1:** Different supply channels for oxygen and other oxidants that may be used by microorganisms to decay organic archaeological material.

Oxygen is the most reactive and powerful oxidant and some decay processes such as fungal attack will only take place when oxygen is available (Figure 1). In unsaturated soils oxygen is supplied through the air filled pores by diffusion, advection or pressure gradients. Oxygen is also soluble in water and may be supplied by water flowing through the soil, or by diffusion through still water. However, these supply channels are less effective as the oxygen content in water is app. 25 times lower than in air and the diffusion of oxygen through water is more than 1000 times slower than in air. Thereby the preservation of archaeological material becomes highly dependent on the soil water content - the oxygen supply is greatly enhanced when the soil dries and vice versa when the soil gets wetter. Consequently, infiltration of water into unsaturated archaeological layers could be an effective method to increase the soil water content, reduce the oxygen supply and thereby reduce the decay of the archaeological materials.

On the other hand, the water content in the soil may itself influence the reactivity of the organic material and possibly an increased water content could increase the decay rate in very dry soils. Furthermore, the infiltration water may contain some oxygen along with other dissolved oxidants such as nitrate and sulphate that may contribute to the decay of organic material. Finally, an increased water flow through the soil layers could change the soil temperature and increase the leaching of soil constituents that could affect both the archaeology and the water environment. It is necessary to evaluate and compare these possible positive and negative effects, before any general recommendations regarding infiltration may be given.

## Methodology

### Study site and data used

At Bryggen in Bergen the buildings and the soil surface is settling at a considerable rate as a consequence of a lowered groundwater table. In September 2006 a 2½-metre deep testpit was made at the northern end of Bredsgården in order to assess the state of preservation of the deposits in the upper unsaturated part of the soil (Dunlop 2007; Matthiesen 2007b). The testpit was re-opened in October 2010 in order to install supplementary monitoring equipment (Matthiesen and Hollesen 2011). Environmental monitoring data from the testpit are used in this report to investigate how the soil water content influences the availability of oxygen within the soil (Matthiesen and Hollesen 2012). Moreover, to investigate how infiltration of water influences the soil water and oxygen content precipitation data from the metrological station Florida in Bergen is used (available from [www.met.no](http://www.met.no)). Finally soil samples from the testpit are used along with soil samples from the newly constructed dipwell MB39 (Dunlop 2011) (Table 1). The samples 1-4 are used to investigate how changes in soil water content affect the decomposition of the organic material. In addition, the samples 1, 3 and 5 are used to investigate if water containing dissolved oxygen, nitrate and sulphate could cause decay of the organic material. Samples 1-3 has previously been used to study the influence from temperature on decay rate (Hollesen and Matthiesen 2011)

Soil sample	Description	Loss on ignition (% of dry weight)	Porosity (% vol)	Water content (% vol)
1:Testpit layer 8 (3.1 m asl)	Organic-rich sandy layer with timber	20	62	48-63
2:Testpit layer 9 (2.7 m asl)	Alternating layers of lime, charcoal and stone	6	71	66-68
3:Testpit layer 14 (2.1 m asl)	Organic layer, with timbers	35	80	66-68
4:Drilling MB-39-01 (2.1 m asl)	Disturbed fire layer	38		
5: Drilling MB-39-10 (-2.15 m asl)	Sand with a few wood chips, weak H <sub>2</sub> S smell	34		

**Table 1:** The samples in this study, all from Bryggen in Bergen. Each individual soil layer has been thoroughly described by archaeologist Rory Dunlop (Dunlop 2007; Dunlop 2011) using the Norwegian Standard layer recording system. An ultra-short description of the layers is given in the second column. Measurements of loss on ignition and porosity are described in Matthiesen and Hollesen (2011). The water content for samples 1-3 is given as an interval, reflecting the variations measured in situ in the period October 2010 to November 2011 (Matthiesen and Hollesen 2012).

### Laboratory experiments

The decomposition rate of organic materials is difficult to measure real-time in the field and therefore it is most often measured under controlled conditions in the laboratory. The two most common methods used to study decomposition rates under oxic conditions are measurements of

either CO<sub>2</sub> production or O<sub>2</sub> consumption in soil samples based on the assumption that Organic material + O<sub>2</sub> → CO<sub>2</sub>. The oxygen consumption method is used in this study (Matthiesen 2007a). For decomposition under anoxic conditions, this study focusses on nitrate and sulphate reduction, where bacteria oxidize organic material by reducing nitrate (NO<sub>3</sub><sup>-</sup>) to nitrogen gas (N<sub>2</sub>) and sulphate (SO<sub>4</sub><sup>2-</sup>) to sulphide (H<sub>2</sub>S). Here there exist a range of methods to measure the nitrate and sulphate reduction rate, including methods using radioactive tracers, but we have used a relatively simple setup where nitrate and sulphate is added to the system and their concentrations are followed over time – a similar setup has earlier been used to measure sulphate reduction rate for samples from the harbour front of Bryggen (Bioforsk 2008).

The oxygen consumption was measured in the collected samples (Table 1) at different water contents to investigate the sensitivity of the decay processes to changes in soil water content. Measurements were made at 15 °C. The first series of measurements were made at in-situ water contents on 8-11 replicates of soil samples 1-4. The samples were transferred to 4.0 ml vials and flushed with atmospheric air before the vials were closed with airtight lids. The oxygen consumption was subsequently measured by monitoring the decrease of headspace O<sub>2</sub> concentrations a week by using oxygen optodes from PreSens ([www.presens.de](http://www.presens.de)). After the first series of measurements the replicates were dried at 15 °C until app. 30 vol% of the soil water remained. Then different amounts of water were added to the replicates and after 48 hours of incubation a new series of measurements was initiated. One replicate was oven dried at 50 °C to remove all water, in order to get a zero reference, and in another replicate the soil was covered by water in order to get a “waterlogged” or 100% reference. The measurement period varied between a few days and up to a month, depending on the reactivity of the soil.

The oxygen consumption measurements were used to calculate the Oxygen consumption rate:

$$\text{Oxygen consumption rate} = V \cdot C \cdot (\Delta O_2 / \Delta t) / m \cdot 100 \quad (1)$$

where V is the volume of air inside the vial (cm<sup>3</sup>), C is the initial concentration of oxygen (mg/cm<sup>3</sup>), ΔO<sub>2</sub>/Δt is the decrease in oxygen saturation over time (%sat/day – taken as the slope of the curves in Figure 6), m is the dry weight of the soil sample (g) and 100 (%) is a scale factor.

The nitrate and sulphate reduction was measured on samples 1, 3 and 5 at room temperature (23 °C). Approximately 30 g of soil with in situ water content was placed in 133 mL vials with oxygen sensors and airtight lids. Initially the oxygen consumption in air was measured as described above. After 1 day, the vials were filled to the rim with demineralised water that had been bubbled with



atmospheric air. The vials were closed and the oxygen consumption in water was measured. After one or a few days the water in the vials was (close to) anoxic, and nitrate was added to a concentration of approximately 20 ppm. The decrease in nitrate concentration was followed over time, by taking 5 mL samples from the vials at intervals and replacing by demineralised water. After the nitrate was consumed, sulphate was added to a concentration of approximately 40 ppm (plus the natural sulphate concentration of the samples). Again 5 mL samples were taken at intervals and replaced by demineralised water. All samples were analysed by Ion Chromatography (IC) giving the content of chloride, nitrate and sulphate.

The measured concentrations were compensated for dilution effects from sampling, and used to calculate the nitrate and sulphate reduction rates:

$$\text{Nitrate/sulphate reduction rate} = V \cdot (\Delta C / \Delta t) \cdot 24 / m \quad (1)$$

where V is the volume of water inside the vial (L),  $\Delta C / \Delta t$  is the decrease in nitrate or sulphate concentration over time (ppm/h) – taken as the slope of the curves in Figure 9), m is the dry weight of the soil sample (g) and 24 (h/day) is a scale factor.

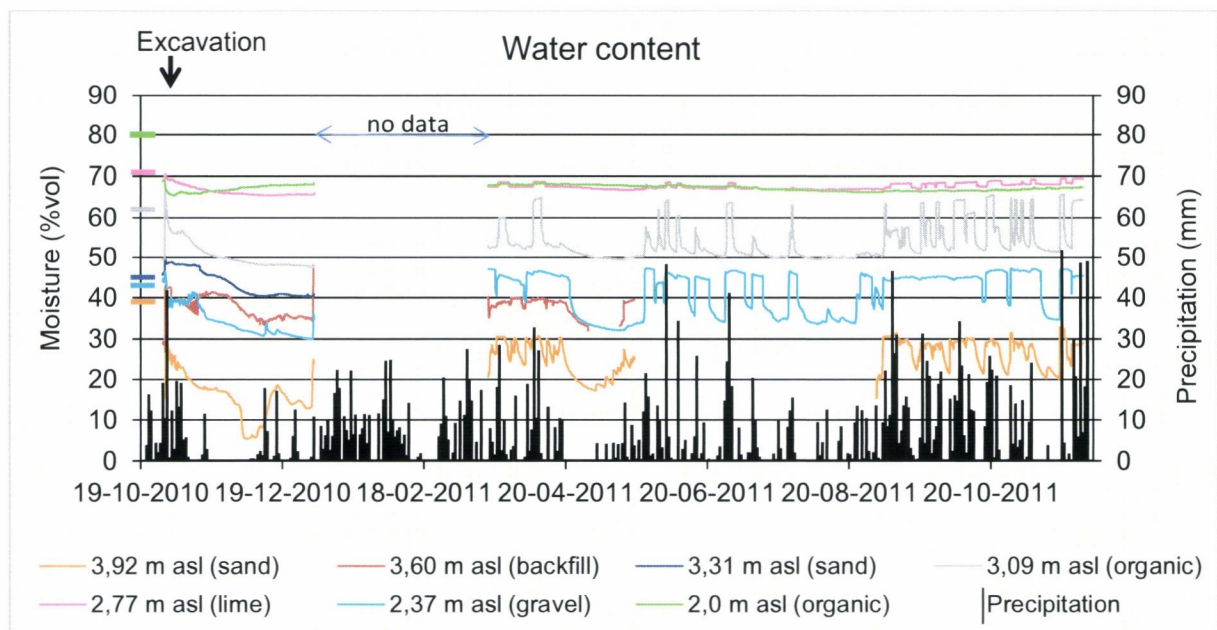
## Results and Discussion

### *Infiltration, water content and diffusion of oxygen through unsaturated soil*

Understanding the coupling between precipitation, infiltration, soil water content and soil oxygen content is important in order to evaluate the possible effect of infiltrating water into the soil. This coupling is best studied in the field, and a good set of data is available from the monitoring at Bryggen in Bergen. The data are described in details in Matthiesen and Hollesen (2012) but some important results are repeated here:

Not surprisingly, the data from Bryggen shows that there is a clear connection between the precipitation and the water content of the different soil layers (Figure 2). 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). This is probably due to differences in the physical properties of the different layers - coarse grained soil material shows a faster response than fine grained material. The data also shows a tendency of decreasing water content in the different soil layers during the period 2006-2010 (Table 2). To some extent this decrease may be a long term effect of drainage in the area but natural variations in the precipitation also seem to play an important role. As seen in Table 2 the yearly mean soil water content is lowest in years with low yearly precipitation rates. The precipitation rates furthermore vary greatly from

year to year (up to 1400 mm or 1400 l/m<sup>2</sup>) which could indicate that great amounts of water may have to be re-infiltrated to the soil to keep it wet during dry years. However, as only a minor part of the precipitation infiltrates into the ground due to the surface pavement a more thorough investigation of the water balance is needed to give a more accurate estimate of the amounts of water needed to keep the soil wet.



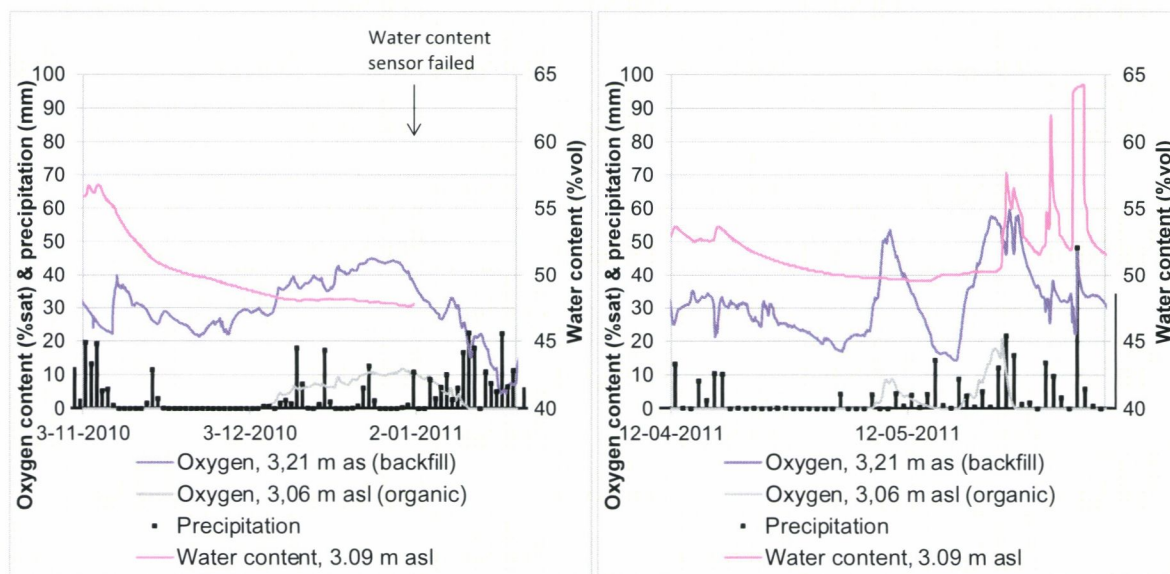
**Figure 2:** Results from water content probes installed at different depths in the cultural layers at Nordre Bredsgården in Bergen (Matthiesen and Hollesen 2012). The soil porosity, as measured in ring samples in the laboratory, is shown with horizontal lines to the left (on y-axis). No ring sample 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).

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

**Table 2:** Yearly precipitation rates for the period 2007-2010 measured at Florida weather station in Bergen. The average water contents measured in the same period at the different soil layers are shown for comparison.

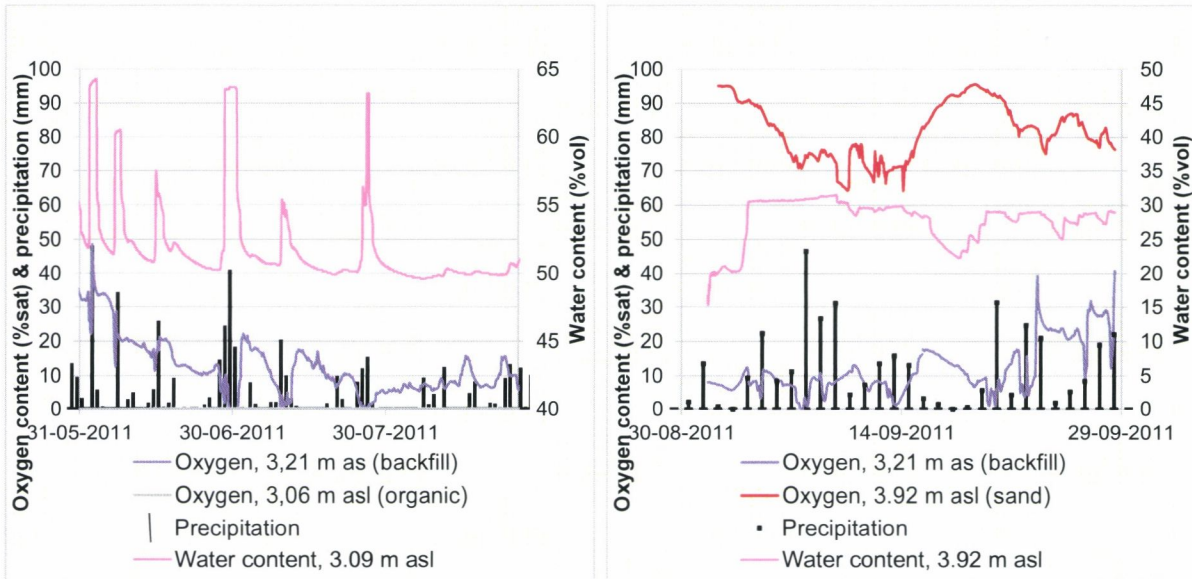
The data from Bryggen gives a good picture of how changes in soil water content influences the oxygen content in the soil. Figure 3 shows how the water content at 3.09 m asl slowly decreases during two dry periods from 17/11-11/12 2010 and 19/4-2/5 2011. In both periods the oxygen concentration increases when the water content drops to a level of approximately 48-50% which corresponds to an air content > 12% (calculated as porosity minus water content). At 2.3 m asl oxygen appears when the water content is below 32% vol, which corresponds to an air content >

11%. Overall, it is estimated that oxygen is mainly present in these soil layers when the air filled volume exceeds approximately 5-15% vol.



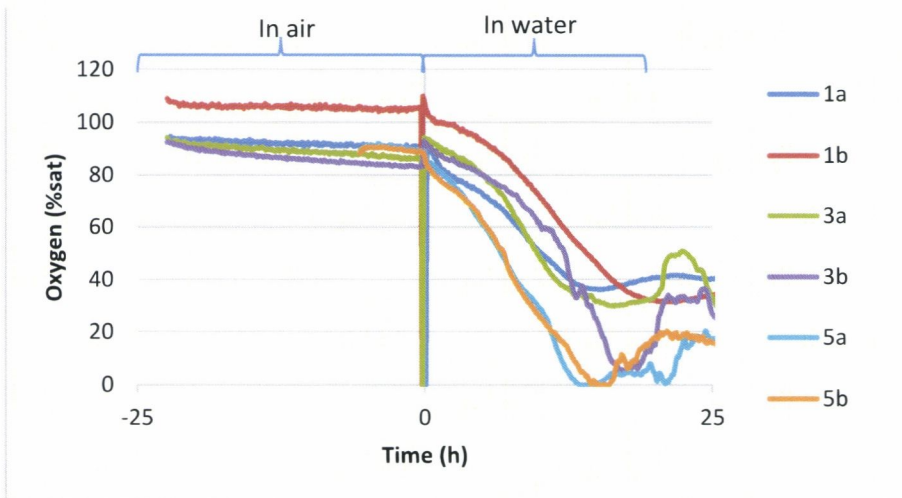
**Figure 3:** Examples of the relationship between water content (measured at 3.09 m asl) and oxygen concentration (measured at the two nearest sensors, at 3.06 and 3.21 m asl) during and after two dry periods. Monitoring data from Bergen (Matthiesen and Hollesen 2012).

In periods with more precipitation the water content increases and the oxygen disappears from the soil. Figure 4 shows some more examples from the monitoring in Bergen: 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 4 (right) shows the results from a water content sensor and oxygen sensor at 3.92 m asl just beneath the soil surface (which is covered by cobblestone at this site) – also here the oxygen concentration decreases during periods with heavy rain.



**Figure 4:** Examples of the correlation between water content and oxygen concentration at different depths, measured during two wet periods. Monitoring data from Bergen (Matthiesen and Hollesen 2012).

The same picture is observed in the laboratory (Figure 5), where the oxygen concentration is measured in a closed vial filled with air (to the left) and with water (to the right). When water is added (at time  $h=0$ ) the oxygen saturation decreases rapidly and after 12 hours the first samples are anoxic. This is due to the fact that the amount of oxygen in water is much lower than the amount of oxygen in air.



**Figure 5:** oxygen concentration measured in a closed vial with soil from sample 1, 3 and 5. At time 0 the vial is opened, filled to the rim with water (in equilibrium with atmospheric air), and closed again.

Overall, this confirms the expected benefits from infiltration of water in the unsaturated zone. It is too early to say exactly how wet the soil should be to keep the soil anoxic - the first data from

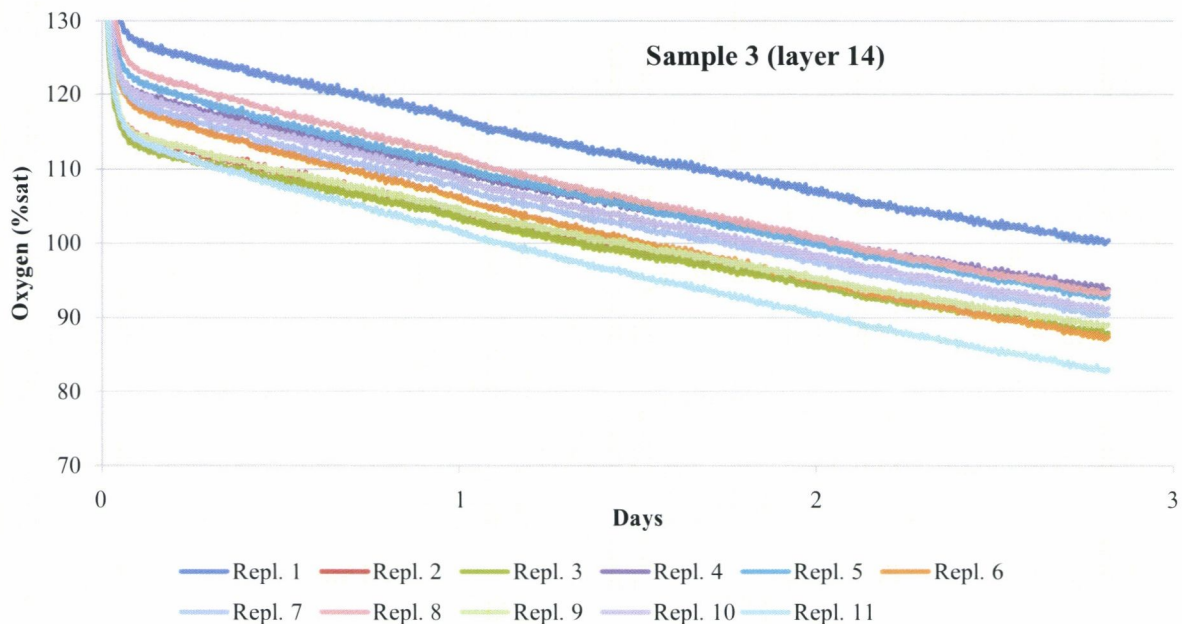
Bergen indicate that the air content should be lower than approximately 5-15% vol to retain anoxic conditions, but more monitoring at Bryggen and other sites is necessary to confirm this.

*Infiltration, water content and reactivity of organic material*

Figure 6 shows an example of the first series of oxygen consumption measurements that were made at in-situ water contents on 8-11 replicates of soil samples 1-4. The oxygen concentration in the vials decreased by approximately one fourth in three days. Overall, the samples showed a good reproducibility and the oxygen concentration decreased (almost) linearly over time, indicating constant oxygen consumption during the experiment. The measured rates for sample 1-3 (Table 3) are in good agreement with previous measurements made by Hollesen and Matthiesen (2011) showing rates of 0.005, 0.004 and 0.033 mg O<sub>2</sub>/g wet soil/day for the three layers respectively.

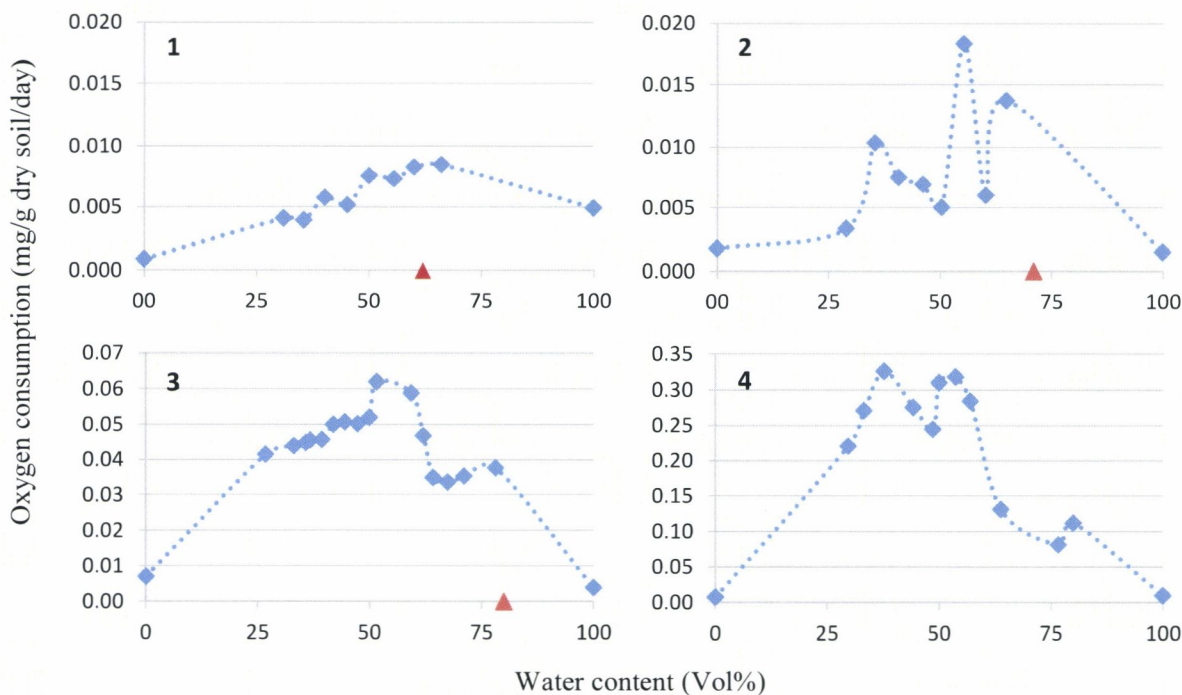
Soil sample	Oxygen consumption rate (mg O <sub>2</sub> /g dry soil/day)	Oxygen consumption rate (mg O <sub>2</sub> /g wet soil/day)
1: Testpit layer 8 (3.1 m asl)	0,010 ± 0,002	0,005 ± 0,001
2: Testpit layer 9 (2.7 m asl)	0,011 ± 0,003	0,005 ± 0,001
3: Testpit layer 14 (2.1 m asl)	0,086 ± 0,006	0,038 ± 0,003
4: Drilling MB-39-01 (2.1 m asl)	0,115 ± 0,024	0,061 ± 0,009

**Table 3:** Reactivity of soil samples from the different soil layers. The reactivity is measured as the oxygen consumption at 15 °C and in-situ water content. The rate is given both relative to the dry weight of the soil (middle column) and relative to the wet weight at in situ water content (right column).

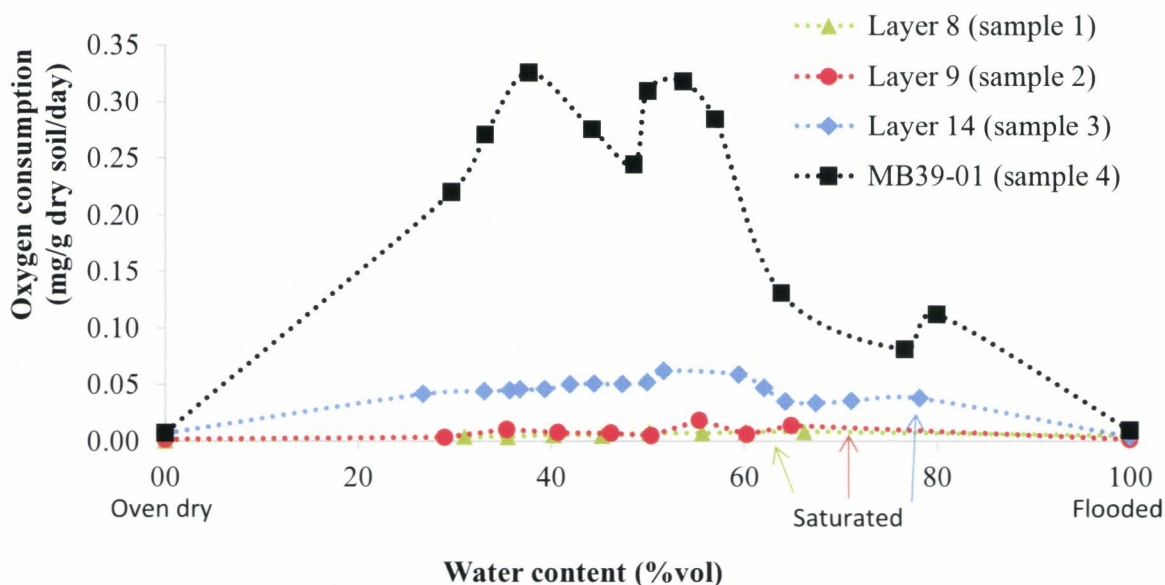


**Figure 6:** Example of oxygen consumption measured at in-situ water content at 15 °C in 11 replicates from soil layer 14 (sample 3).

Figure 7 and 8 shows the oxygen consumption rates at different water contents for all of the investigated soil samples. There is a great difference in the overall rate of oxygen consumption between the two upper layers of the test-pit (sample 1 and 2) and the deeper laying layers (sample 3 and 4) with the deeper layers consuming oxygen up to 30 times faster.



**Figure 7:** Oxygen consumption rates measured at different water contents in samples 1-4. The red triangle on the x-axis shows the porosity of the sample, i.e. the sample is saturated for water contents above this value. A water content of 100% vol is not really possible (would refer to pure water).



**Figure 8:** The data from Figure 4 combined to one figure, emphasizing the difference in reactivity for the 4 samples.

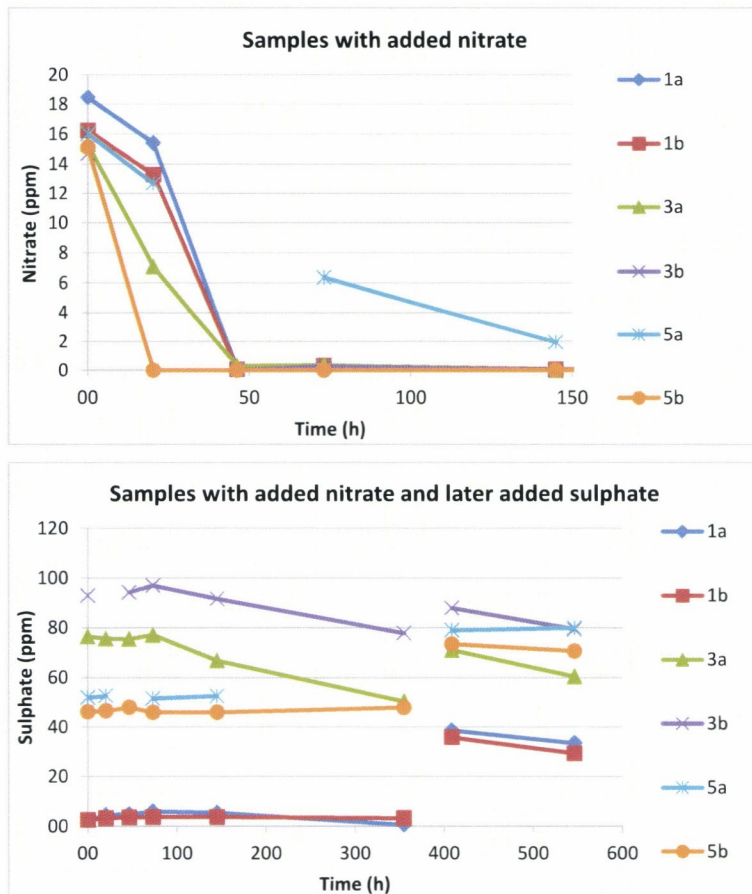
The data shows that there is an influence from the water content on the reactivity of the soil: For very dry samples (oven dried) the reactivity is low, it increases when the soil is wet, and then decreases again when the soil gets very wet (saturated) and even more when the soil is flooded/waterlogged. The highest reactivity has been measured at water contents between 30 and 60% vol. In practical terms the decrease in reactivity for the saturated or flooded soil is a positive effect of infiltration, i.e. an increased water content of the soil not only decreases the oxygen supply as described above, it actually may also decrease the reactivity of the soil. At the other end of the scale the samples with 25-30% vol have been air dried for several days and the reactivity is still relatively high. The samples with 0% water have been oven dried at 50 °C and here the reactivity is very low, as bacterial decay is hampered due to lack of water. Thus at extremely dry sites, as for instance in deserts, the archaeological material may be preserved due to lack of water, and at such places the addition of water may actually increase the decay. It will require further studies to document if this has any practical implications in Norway, i.e. if there are any sites (for instance under heated buildings or church floors) where the decay is currently limited by the lack of water.

#### *Infiltration and supply of dissolved oxidants*

In relation to infiltration of water it has been discussed to which extent oxygen or other oxidants (nitrate, sulphate) dissolved in the water could cause decay of the cultural layers. This will depend on the amount of water added, the concentration of dissolved species in it, and the reactivity of the different oxidants.

As for the reactivity of different oxidants it is a general picture that oxygen is the most reactive, followed by nitrate, manganese oxides, iron oxides, and sulphate (e.g. Froelich et al. 1979).

However, the exact decay rates in cultural deposits are not known. A preliminary study has been made in the laboratory, trying to quantify the decay of samples 1, 3 and 5 under different conditions that may occur in the soil depending on infiltration. Their consumption of oxygen under both unsaturated and waterlogged conditions are shown in Figure 5 and their consumption of nitrate and sulphate are shown in Figure 9. Oxidation by manganese and iron oxides are not included in the study, as they are immobile and will not be supplied by infiltrating water – however, there may be a considerable pool present in the soil that may contribute to microbial decay of organic material after re-saturation of the deposits, and thus postpone the positive effects for a period.



**Figure 9:** Measurements of nitrate (upper) and sulphate (lower) concentrations over time. Nitrate is added to the vials at time 0 h and sulphate is added at 400 h.

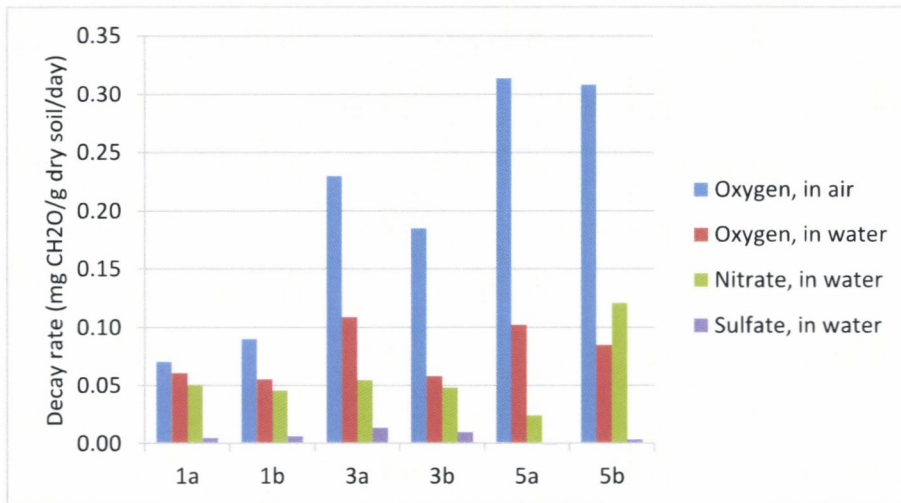
Based on the decreasing oxygen, nitrate and sulphate concentrations it is possible to calculate a consumption rate (Table 4)

		1a	1b	3a	3b	5a	5b
Oxygen, in air	mg/g dry soil/day	0.075	0.096	0.246	0.198	0.335	0.329
Oxygen, in water	mg/g dry soil/day	0.065	0.059	0.116	0.062	0.109	0.091
Nitrate, in water	mg/g dry soil/day	0.084	0.076	0.091	0.080	0.041	0.202
Sulfate, in water	mg/g dry soil/day	0.008	0.010	0.022	0.016	<0.001	0.006

**Table 4:** consumption rate for different oxidants. All are given relative to the dry weight of the soil. All measurements have been made at room temperature (23 °C).

In order to compare the different oxidants in Table 4 on an equal basis, the numbers are recalculated to the amount of organic material (represented as CH<sub>2</sub>O) they may oxidise (Figure 10).

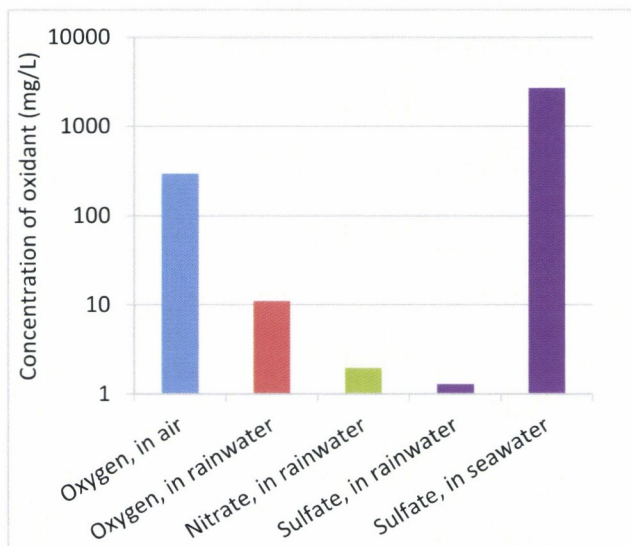




**Figure 10:** Comparison of decay rates for organic material in soil samples from Bryggen, measured under different conditions in the laboratory at room temperature (23°C). “Oxygen in air” represents drained conditions, whereas “Oxygen/nitrate/sulphate in water” represents waterlogged conditions with unlimited supply of the three different oxidants.

Figure 10 confirms that oxygen is the most reactive oxidant, and it is noted that the decay rate “in air” (i.e. under drained conditions) is higher than in all the other setups, i.e. “any water is better than no water”. Still, the decay rate shown for both dissolved oxygen and nitrate is significant and their effect in situ will depend on the amounts that are added. The sulphate reduction rates found here are considerably lower, but still correspond to a decay rate of 0.003-0.013 mg organic material pr. g dry soil per day, which would normally be considered poor or lousy preservation conditions (PresCon 1-2). These experiments have been made at 23 °C which may give an unrealistic high decay rate, but on the other hand it is possible that the rate would increase over time as a larger population of sulphate reducing bacteria becomes established in the soil (the bacteria are strictly anaerobic and during the experiments under oxic conditions they have only survived in small anoxic parts of the soil). The sulphate reduction measured is on the same level as was found by (Bioforsk 2008) who measured sulphate reduction in 8 samples from the harbour front of Bryggen and found a consumption rate corresponding to 0.003-0.015 mg organic material pr. g dry soil per day at 10 °C. For comparison, the decay rate in the central part of Bryggen, where there is a very slow water exchange and the decay is dominated by methanogenesis, has been estimated to only 0.0001 mg organic material/g/day (Matthiesen 2009) i.e. 1 or 2 orders of magnitude lower.

Apart from the reactivity, the supply of the different oxidants is extremely important – if a given oxidant is only present in a limited concentration (Figure 11) or for a limited period it may be less important:



**Figure 11:** Examples of concentration of different oxidants – see text for details. Note logarithmic scale.

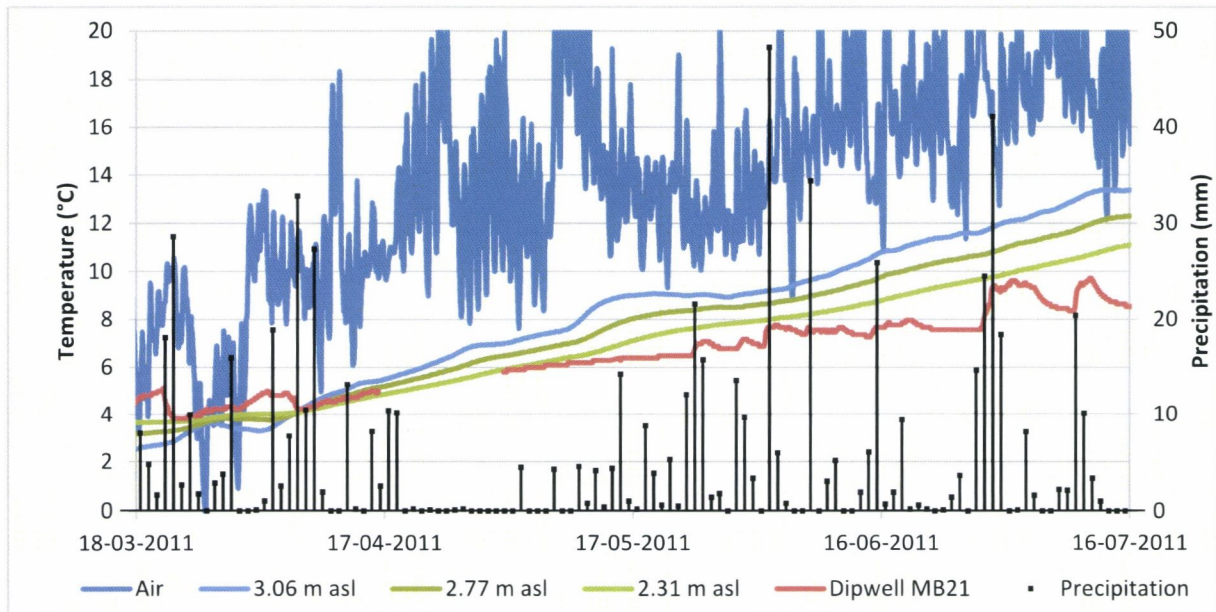
As for oxygen in air, the concentration in atmospheric air is 289 mg/L (at 10 °C) and its presence has already been discussed above based on the field measurements from Bergen. As for oxygen in water, the maximum concentration of dissolved oxygen is 11 mg/L (at 10 °C) when water is in equilibrium with atmospheric air. Figure 4 showed some examples of oxygen measurements in the unsaturated zone on Bryggen in wet periods. This showed a decrease in oxygen concentration in the unsaturated zone during heavy rain, so 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. It indicates that the oxygen dissolved in rainwater is reduced or used up before it reaches even the uppermost oxygen sensors at this site. This is also indicated by analysis of groundwater from dipwells on Bryggen showing anoxic conditions in the saturated zone for the large majority of dipwells (Matthiesen 2005; Matthiesen 2008). An exception is a dipwell called MB5, next to the sheet piling on Bryggen: here it has been shown that the normal anoxic conditions become oxic during heavy rain, indicating that the water flow around this dipwell is so fast that the dissolved oxygen isn't used up during its transport through the soil (Matthiesen, 2005). Under such conditions the decay rates given in Figure 10 as "oxygen in water" may be relevant in the saturated zone.

As for nitrate, information about the concentration in rainwater measured at 6 different stations in Norway during 2009 is given in (Hjellbrekke and Fjæraa 2011). Extreme values of up to 30 mg NO<sub>3</sub>/L have been measured on a few occasions, but the yearly average concentration varies between 0.2 and 2 mg NO<sub>3</sub>/L at the 6 stations. At this stage it is therefore estimated that the supply of nitrate through rain is lower than the supply of dissolved oxygen. Nitrate hasn't been measured in soil water from the unsaturated zone, but concentrations up to 6 mg/L has been measured in the most dynamic dipwells on Bryggen (Matthiesen, forthcoming). This could indicate that there are some additional nitrate sources in the area, for instance from de-icing salts or road runoff.

As for sulphate the yearly average concentration measured in rain in Norway in 2009 varies from 0.4 to 1.3 mg SO<sub>4</sub>/L (Hjellbrekke and Fjæraa 2011). However, the sulphate supply is highly dependent on the input of seawater, where the concentration is as high as 2700 mg/L (Figure 11), i.e. even a small input of seawater (from aerosol, groundwater flow, or active infiltration of seawater) will greatly enhance the input. Furthermore, there may be a production of sulphate in the soil, if reduced sulphur species are oxidised. Most dipwells on Bryggen show a sulphate concentration between 1 and 10 mg/L (Matthiesen forthcoming), but in the drained area some dipwells contain 10-100 mg/L (probably due to oxidation of reduced sulphur), and at the harbour front up to 1000 mg/L has been found (due to seawater intrusion). This means that even if the reactivity of sulphate may be 10 times lower than the reactivity for nitrate and oxygen, it cannot be recommended to use for instance seawater for infiltration as the concentration of sulphate may be more than 100 times higher than the concentration of the other dissolved oxidants. To sum up, the potential damage from dissolved oxidants in the infiltration water depends on both the composition of the water and the amount flowing through the deposits. If the flow rate is very low (stagnant conditions) the different oxidants will be used up over time, after which the decay rate becomes very low - in other words “stagnant conditions is better than a large water exchange”. Before initiating infiltration it is thus recommended that the water quality and the flow rate is investigated, and compared to the reactivities presented in Figure 10.

#### *Other effects from infiltration*

Infiltration of water may in theory influence the deposits in numerous ways, but it has not been possible to evaluate all of them within the frame of this report. One effect we were asked to consider was the possible influence on soil temperature. Again data from Bryggen in Bergen is used in the evaluation:



**Figure 12:** Temperature measurements at different depths in the unsaturated and saturated zone at Nordre Bredsgården in Bergen (data from Matthiesen and Hollesen 2012). In the unsaturated zone temperature sensors were placed directly in the soil, and in the saturated zone a data logger was placed in dipwell MB21. Air temperature and precipitation is also shown. Soil surface is at 4.14 m asl and groundwater level varied between 1.0 and 2.2 m asl in the period shown.

Figure 12 shows how precipitation influences the soil and groundwater temperature. The most marked effect is seen in the groundwater (dipwell MB21) for instance in the beginning of July, where the groundwater temperature increases abruptly by 2 °C due to rain. In the unsaturated zone no such effect from the precipitation is seen – here the soil temperature just follows the trend in air temperature with some delay. The temperature of the precipitation has not been measured directly, but it is expected to follow the air temperature, i.e. during winter the precipitation is colder than the soil, and during summer it is warmer than the soil. A temperature increase of 2 °C may increase the decay rate by 15-20% (Hollesen and Matthiesen 2011) which is considered of less importance compared to the benefits from the rain on soil moisture. Still it cannot be recommended to use very warm water for infiltration.

Within the frames of the present project, it has not been possible to evaluate the effect from infiltration on leaching (“washing out”) of the deposits or artefacts, but it is recommended to initiate such a study. Furthermore, in this report the focus has solely been on the preservation of organic remains. At sites containing for instance metals or bones some additional effects need to be evaluated, as for instance the effect of chloride on metal corrosion.

## Conclusions and future work

In order to sum up:

- The effect from infiltration on soil moisture and oxygen supply has been studied using monitoring data from Bryggen, where it was demonstrated how the oxygen concentration in the soil increased during dry periods (Figure 3) and decreased during wet periods (Figure 4)
- A first estimate has been made of “how wet is wet enough” to keep the soil anoxic – it depends on the soil type, but monitoring data from Bryggen showed anoxic conditions when the air content of the soil (i.e. the soil porosity minus the water content) was lower than 5-15% vol
- Under oxic conditions the highest decay rates were found at “medium” water contents between 30 and 60% vol for the samples investigated. The rates were lower under saturated conditions and even lower under flooded conditions (Figure 8)
- Under very dry conditions (oven dried samples) the decay was limited by lack of water (Figure 8), but it requires further studies to see if this has any practical implication in Norway, were the soil is normally humid to wet.
- The effect of dissolved oxygen, nitrate and sulphate in the infiltration water has been evaluated, showing that the decay will depend on both the amount and type of water:
- As for dissolved oxygen, the reactivity is high (Figure 10) but the concentration low (Figure 11). Data from the unsaturated zone in Bryggen shows that oxygen dissolved in rain hardly reaches the cultural layers and even during heavy rain the oxygen concentration in the soil decreases rather than increases (Figure 4). However, in the saturated zone there is one dipwell with a very high water exchange (MB5) where oxygen-rich water actually reaches the waterlogged deposits during heavy rain (Matthiesen 2005)
- As for nitrate the reactivity is high (Figure 10) but the concentration low (Figure 11), and it is expected to follow the pattern seen for oxygen
- As for sulphate, the reactivity is fairly low, but the concentrations can be very high (Figure 11). The decay rate measured for soil samples in a sulphate rich environment (Figure 10) was 1-2 orders of magnitude higher than what is found in the most stagnant areas on Bryggen.
- The effect from infiltration on soil temperature is estimated to be limited (Figure 12) unless very warm or cold water is used
- Overall, this investigation has confirmed the rules of thumb that “any water is better than no water” and “stagnant water is better than a large water exchange”
- The effects on leaching and on inorganic materials have not been addressed in this study.

Future work should include

- Evaluation of typical infiltration rates – how much water is expected to be used?

- Evaluation of the composition of specific water types that may be used for infiltration, such as for instance road run-off or roof run-off.
- Further investigation of the correlation between water content and oxygen penetration: how wet should the soil be to keep the conditions anoxic
- Investigation of leaching – will the cultural deposits and artefacts be “washed out” by infiltration?
- Evaluation of the effect on other types of archaeological material, such as for instance metal or bones

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