

# MONITORING MITIGATION MANAGEMENT

THE GROUNDWATER PROJECT - SAFEGUARDING THE  
WORLD HERITAGE SITE OF BRYGGEN IN BERGEN





Prosjekt  
Bryggen



United Nations  
Educational, Scientific and  
Cultural Organisation



Bryggen  
inscribed on the World  
Heritage List in 1979

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# DEDICATION, ANN CHRISTENSSON

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In loving memory of our Ann  
who thought of Bryggen as a bunch of delicate blossoms  
and knew that its continued well-being  
depends on getting the right mix of soil and water.

This project and this publication owe a great deal to her  
labours and love, and we are very glad and grateful that  
she got to hear that the initial results were encouraging.  
We promise to keep tending those flowers for you, Ann.



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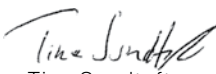
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## MESSAGE FROM MINISTER OF CLIMATE AND ENVIRONMENT

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World Heritage Site Bryggen in Bergen is one of our most important historical monuments and one of the country’s most popular tourist destinations. The Ministry of Climate and Environment has overall responsibility for the upkeep of Norway’s world heritage sites and has kept a close eye on the work at Bryggen in Bergen for a number of years. In 2011 a sum of NOK 45 million was allocated for planning and implementing measures to tackle the problems at Bryggen. Since then we have received regular reports documenting steadily rising groundwater levels and declining rates of subsidence. Sustainable systems of water management ensure that all the available surface water is channelled to where it is needed for infiltration purposes. The methods that have been employed are designed to be resilient in the face of climate change, and can easily be modified for implementation in other Norwegian centres. Our grateful thanks to all who, through the application of modern technology and innovative solutions, have contributed to the present efforts to ensure the survival of this iconic monument.



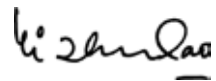
Tine Sundtoft  
Minister of Climate and Environment

## MESSAGE FROM UNESCO

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The Bryggen World Heritage Site has been suffering from severe, long-term subsidence caused by groundwater drainage. By combining geological mapping, groundwater monitoring and modelling, along with geotechnical, geochemical and archaeological investigations, the systematic and interdisciplinary Groundwater Project has been instrumental in re-establishing groundwater levels and combating the insidious threats of subsidence and decay.

This publication presents the results from this important work, which will without doubt contribute significantly to the conservation of other UNESCO heritage sites throughout the world.



Kishore Rao  
Director, Division for Heritage &  
World Heritage Centre  
Culture Sector

# NEW KNOWLEDGE SAVES BRYGGEN IN BERGEN

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In 2011 we started a rescue mission for Bryggen, the old wharf, in Bergen. The work was financed by the Norwegian Government, following a recommendation from the Ministry of Climate and Environment. The preparations and the work itself have been carried out by several Norwegian and international institutions. All of which have been involved in a groundbreaking project that has been crowned with success.

The UNESCO cultural heritage site, Bryggen in Bergen, consists of much more than what meets the eye. Beneath the rows of wooden buildings archaeological deposits tell the tale of Bryggen’s 1000-year long history. Today, Bryggen’s appearance stems from the time after a devastating fire in 1702. But Bryggen was ruined by at least seven large fires throughout the centuries. Each time Bryggen was rebuilt on top of its old foundations and refuse. This has left us with, in some places, 10 meters thick archaeological deposits under Bryggen.

By the turn of the 21st century we could observe that the old wooden buildings were suffering from severe subsidence. After initial monitoring and research we could conclude that a leaking sheet pile wall at a neighbouring hotel site was the cause of the problem. Groundwater was leaking away from Bryggen and into the hotel site, resulting in decomposition of the archaeological layers underneath Bryggen.

Repairing the sheet pile wall would only be part of the cure for Bryggen. More important, the levels of groundwater had to be raised and reestablished. And new methods had to be established to secure a sustainable supply of water to the ground beneath Bryggen. The damage to the archaeological deposits can never be repaired. But today we may conclude that the groundwater beneath Bryggen has been raised and the subsidence has been reduced to a natural rate. And through new and groundbreaking methods we have secured the site’s groundwater level for the foreseeable future.

Bryggen in Bergen is amongst Norway’s most important cultural heritage sites, and I would like to thank all who have contributed to the work for the past four years. This book is a testament to your knowledge and inventiveness. Congratulations all.



Jørn Holme  
director general  
Directorate for Cultural Heritage



# INTRODUCTION

Jens Rytter & Iver Schonhowd, Directorate for Cultural Heritage Norway

What we see standing at Bryggen today is the long rows of wooden buildings (tenements) running perpendicularly to the waterfront. These were features typical of most Northern European harbour towns, but the fact that it has survived the ravages of time makes Bryggen in Bergen virtually unique. It is the best preserved monument to Hanseatic trading activities in the North Sea and Baltic regions, activities and connections that have been well documented through extensive archaeological excavations and detailed historical and architectural research. The fact that Bryggen was the seat of one of the major Hanseatic overseas settlements along the North and Baltic Sea, and outlasting by far all the others, is a measure of its importance.



Figure 1

Figure 1 Bryggen in Bergen and the other towns with Hanseatic privileged enclaves: London, Bruges and Novgorod.  
Map: O.M. Hansen, Alkymi Design.



Figure 2



Fig.2.

The standing buildings, together with the deposits that support them, narrate the story of Bryggen's emergence and development over the past 1,000 years. This unparalleled combination constitutes the basis for Bryggen's status as a World Heritage Site.

The ground beneath the wooden tenements, which were erected after the last city-wide fire in 1702, is made up of invaluable archaeological deposits - many of which contain a high proportion of organic material - reaching thicknesses in excess of 10 metres in places. These deposits encapsulate the entire history of the settlement and the people who lived and worked in it. Interleaved among the occupation and refuse strata are numerous firelayers, the remains of the all-too frequent fires that razed parts or all of the Bryggen area.

Figure 2 Overview of Bryggen in Bergen.  
Drawing: T. Sponga, © Riksantikvaren.

For a wooden settlement like Bryggen, fire has always been the most immediate hazard. Since around 1900, however, urban renewal has become a more insidious and potentially equally potent threat to the historic buildings' survival, fuelled in some periods by an antipathy among the townspeople themselves. In the first decades of the 20th century, the entire southern half of the original settlement was indeed torn down - a fate that the northern half could easily have shared in the middle of the century.

By the end of the 20th century, it had become apparent that the buildings were suffering from severe subsidence, and surveying of fixed measurement points showed that the rate of subsidence in some parts of the site was alarming. It did not take long to identify a likely causal train: simply stated, loss of groundwater, leading to decay of organic matter in the archaeological deposits, resulting in accelerated subsidence.



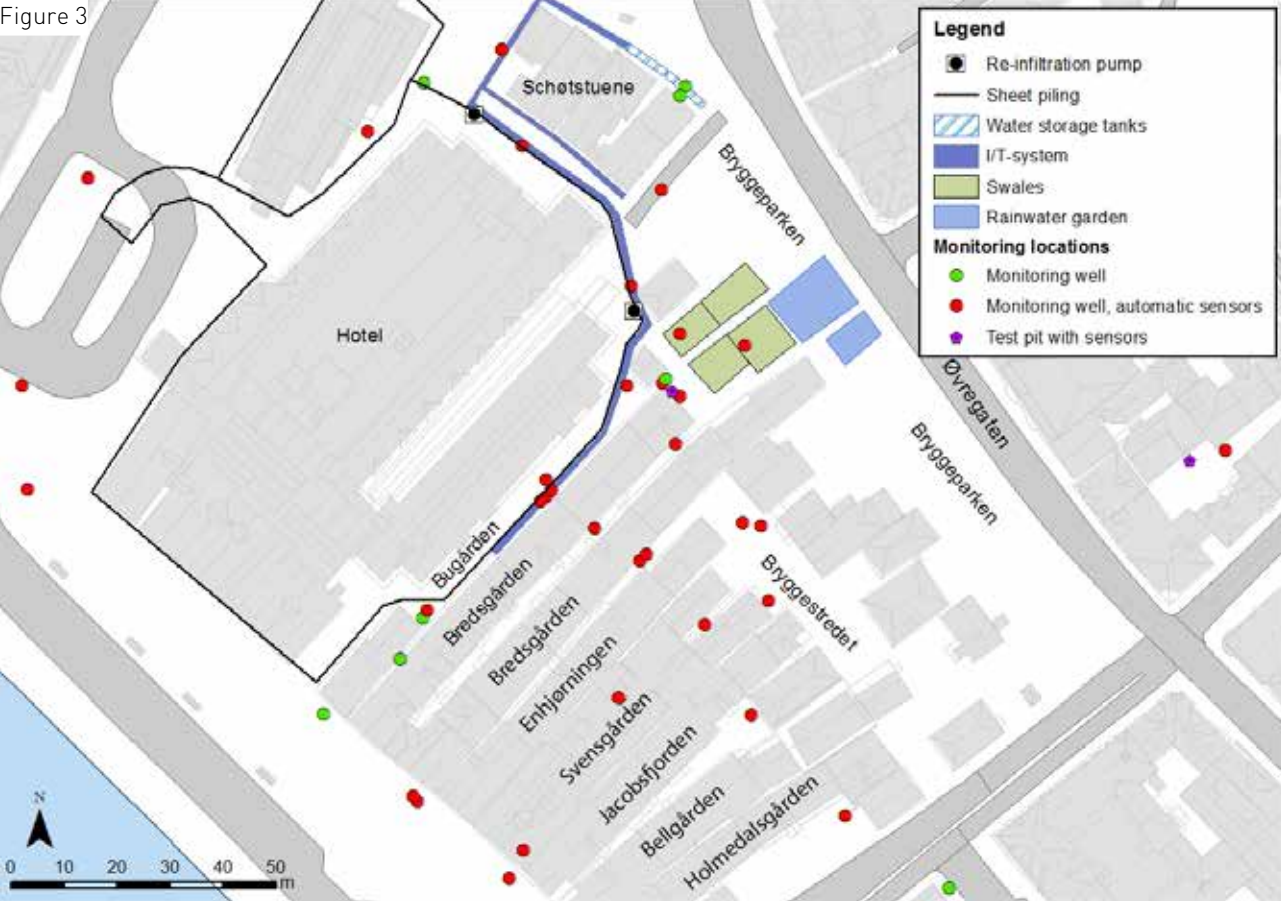


Figure 3 Map of mitigation measures carried out by the Groundwater Project.  
Map: A. Seither, NGU.

Riksantikvaren (Norway’s Directorate for Cultural Heritage) moved quickly to establish a monitoring programme to map, analyse and interpret the site’s subsurface situation: the state of preservation of the archaeological deposits, the preservation conditions in the deposits, and the complex hydrogeological system. The programme soon established a firm link between the loss of groundwater and the documented damages to the buildings and deposits, and identified drainage of groundwater into the neighbouring hotel site as the principal cause of the problem.

In the spring of 2011, following a recommendation from the Ministry of Climate and Environment, Norway’s Parliament approved an extraordinary allocation of NOK 45 million to combat the problem. Parliament, via the ministry, assigned Riksantikvaren with overall

responsibility for the task of raising groundwater levels and reducing rates of organic decay and, ultimately, subsidence, but with the proviso that the work should entail negligible removal of intact archaeological deposits.

Riksantikvaren recruited a variety of specialists to form an advisory team, and engaged Statsbygg (the Directorate of Public Construction and Property) to direct and coordinate the work. In this book, the individual experts present aspects such as challenges, methods, results and solutions with regard to their own particular fields. In addition, a historian and an archaeologist were invited to write the two opening chapters to put our work in a proper historical context.

After four years of mitigation work, we can now conclude that most of the goals have been reached. Groundwater loss has been greatly reduced and groundwater levels have been raised considerably in sizeable portions of the most badly affected area. Rainwater from roofs and surfaces is infiltrated in various ways into the ground rather than disappearing uselessly into the municipal drainage system, and the preservation conditions in substantial volumes of archaeological deposits have been



Figure 4 Passageway between two building rows making up a double tenement - preserved medieval building pattern at Bryggen. Riksantikvaren’s archive.  
Photo: A. Kjerseim.

either stabilized or improved. Subsidence of the buildings and ground has been reduced to a virtually natural rate. However, no matter what we do, the damage suffered by the archaeological deposits since the building of the hotel cannot be reversed, nor can we ever re-establish the original hydrogeological conditions. Infiltration will continue to be necessary for the foreseeable future in order to maintain the area’s water balance, and we have opted for infiltration solutions that will ensure the most sustainable water supply, and will be resilient in the face of climate change. Continued monitoring will enable us to keep a close eye on trends and changes.

There are some areas where groundwater levels have not been raised. This is in most cases due to the fact that these areas contain archaeological remains - medieval stone ruins, or burials - where water saturation is not beneficial. The only goal that has

not been either completely or partially attained, and probably never can be, is reduction of groundwater temperature. However, when compared to the importance of keeping groundwater levels and water content in the archaeological deposits high, temperature is not considered a priority factor.

Without the expertise of the individuals and institutions making up the advisory team, we could never have achieved the results reflected by the contents of this book. Riksantikvaren wishes to extend its grateful thanks to the Norwegian Institute for Cultural Heritage Research (NIKU), the National Museum of Denmark, the Geological Survey of Norway (NGU), Multiconsult AS, Norconsult AS, MVH Consult, Tauw (Netherlands), and the Free University of Amsterdam for their contributions to the Groundwater Project and to Statsbygg for its able direction of the work.

Finally, we wish to commend in particular Rory Dunlop, NIKU, for his enthusiastic and creative efforts in text vetting, translation and much more, and Elin Rotevatn, Riksantikvaren, for her many excellent contributions, not least in connection with coordination and organization of the publication process.



# 01

THE HISTORY OF BRYGGEN UNTIL C. 1900

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Geir Atle Ersland  
University of Bergen





Figure 1.1

Figure 1.1 Detail from Johan Joachim Reichborn's drawing of 'Handels Contoirtet udi Bergen' in 1768. The Bryggen tenements are numbered 1 – 7 and 9 – 18. 1. Finnegården, 2. Dramshusen, 3. Bratten, 4. Leppen, 5. Revelsgården, 6. Sologården, 7. Kjøpmannsstuen, 9. Kappen, 10. Holmdalen, 11. Jakopsfjorden, 12. Svensgården, 13. Enhjørningen, 14. Bredsgården, 15. Bugården, 16. Engalgården, 17. Søstergården, 18. Gullskoen. Compare to figure 5. (The original drawing is kept at Bergen Byarkiv).

## BRYGGEN AS PART OF THE PRESENT-DAY TOWNSCAPE

Bryggen's status as an internationally renowned heritage monument can be argued from two overarching perspectives. Firstly, the building pattern of long, narrow tenements running perpendicular to the wharf represents the typical Northern European medieval harbour town. Bryggen is unique in having managed to retain this structure, which today is found hardly anywhere else.

Secondly, Bryggen was for more than 400 hundred years a main hub for the Hanseatic trade in the North Sea and Baltic regions. Bryggen is the best-preserved settlement testifying to this trade.

When referring to Bryggen as a heritage monument, one usually refers to a confined area comprising the buildings and the underlying archaeological deposit. However, this leaves out elements that are central to the understanding of Bryggen in its urban context. Firstly, Øvregaten (the



medieval High Street) is vital for defining the Bryggen area. Secondly, St. Mary’s Church, which was a prominent parish church for both the pre-Hanseatic Bryggen and the Hanseatic Kontor. And thirdly, the wharf and harbourfront, which is the defining element of Bryggen. The name derives from Old Norse Bryggjum, as found in the Town Law.<sup>1</sup> The name underlines the link between the tenements and the harbour. The infilling and construction of wharfs in front of the tenements started in the 12th century, and the latest contributions in the 1930s were part of the same process. The wharf and harbour is the *raison d’etre* of the Bryggen heritage.

## BRYGGEN AS PART OF THE OLDEST TOWN NUCLEUS

The oldest written sources that mention the origin of Bergen are the Norse sagas, where it is stated that King Olav Kyrre (1067-93) founded Bergen.<sup>2</sup> In the town’s first written history, the Bergens Fundas (c. 1560), we are told that some fishermen’s huts occupied part of the site at the time the king founded the town.<sup>3</sup> The anonymous author of Bergens Fundas gave rise to the idea that there existed a pre-urban settlement prior to the founding. In his history of Bergen, written in the latter part of the 17th century, Edvard Edvardsen drew a map where he reconstructed medieval Bergen and indicated that the first houses were built in the northern part of the Bryggen area. In modern historiography, Munch (1849) proposed the pre-urban phase as common to all Norwegian medieval towns.<sup>4</sup> Storm (1899) refuted this and argued that the earliest towns in Norway had been established as urban centres from scratch.<sup>5</sup>

The idea of a pre-urban settlement was given a detailed evocation by Koren Wiberg. He suggested a planned pre-urban settlement with a morphological pattern echoing that of the later Bryggen tenements.<sup>6</sup> His writings and his artistic drawings had a profound impact not only on the popular view regarding the origins of Bergen, but also on schooled interpreters.<sup>7</sup> Koren Wiberg’s hypothesis was challenged by Lorentzen, who supported Storm’s viewpoints and argued that the foundation had taken place in the vicinity of the later Church of St. Mary.<sup>8</sup>

The archaeological excavation carried out after the Bryggen fire of 1955 presented an opportunity to test the viewpoints of Koren Wiberg and Lorentzen. However, this massive archaeological effort was not able to throw conclusive light on the question of the earliest origin

of Bergen. The excavation’s director, Herteig (1969), concluded that signs of activity could not be traced further back than the first part of the 12th century.<sup>9</sup>

Helle presented an in-depth analysis of the written sources and the historiographical tradition in his *Bergen bys historie* (1982). He combined the sagas’ version with the hypothesis of a pre-urban settlement and concluded that Bergen most likely had its origins prior to King Olav Kyrre, and that urban growth gained momentum in the following decades.<sup>10</sup>

Krzywinski and Kaland (1984) published results from a series of botanical analyses, which indicated a denser settlement than one should expect from only rural activities in the area prior to 1100.<sup>11</sup> This was followed by Hjelle (1986) who presented an analysis of organic material from the Veisan area, material dated to the period stretching from the late 8th to the 10th centuries, and concluded that this might be labelled as traces from a permanent marketplace.<sup>12</sup> Dunlop (1985) followed by Myrvoll (1987) suggested that the earliest urban settlement had two nuclei, one in the northern part of the Bryggen area and one further south in Vågsbotn, and that the two merged in the 12th century.<sup>13</sup> Hansen (2005) has suggested that the earliest founding took place c. 1030.<sup>14</sup> The empirical support for Hansen’s hypotheses has been questioned by Helle, and the issue of Bergen’s origin is still undecided<sup>15</sup>

## PROPERTY PATTERNS AND OWNERSHIP

There has been a strong emphasis on trade when it comes to explaining why Bergen was established and prospered as an urban centre. However, urban development in medieval Norway as well as in other regions was a process running parallel to political unification of a larger territory, and the conversion to the Christian faith. Bergen soon became a centre of both secular and ecclesiastical power and as such an important arena for the social elites. This in turn attracted crafts and tradesmen, and since Bergen was ideally located between the northern Norwegian stockfish-producing region and the growing market for this produce on the Continent and the British Isles, Bergen became a hub for the most extensive segment of Norway’s commerce during the Middle Ages.<sup>16</sup> This in turn attracted foreign tradesmen, among whom the Hanseatic merchants were the most prosperous.

In the late 17th century we find that for every tenement plot at Bryggen, ownership can be traced back to either medieval ecclesiastical institutions or aristocratic families.<sup>17</sup> The historians of the 16th century proposed that the tenements at Bryggen came into the possession of the Hanseatic merchants when they established their privileged enclave at Bryggen. Both the Bergens Fundas and Absalon Pedersson (c. 1570) tell of townspeople who were not able to repay money borrowed from the Hanseatic merchants and therefore had to give away their buildings. A plausible interpretation is that the tenements belonged to ecclesiastical and secular landed estates.

A primary function of the tenements was to have access to the commercial activities in Bergen, and to trade the surplus from the rural estates and take part in the growing European demand for stockfish.

A secondary function was for the land-holding aristocracy to be represented in Norway’s largest political centre. The Hanseatic takeover of tenements at Bryggen can be seen as the result of profound structural changes related to the demographic and agrarian crises following the outbreak of plague in 1349. The demographic decline reduced the surplus and revenues from the landed estates in Western Norway, and made the tenements redundant except for letting out the buildings to the growing group of Hanseatic merchants. In the long run tenement owners might have found it costly to maintain their properties and more profitable to rent out the tenement plot in exchange for an annual rent.<sup>18</sup> In the 16th century all the tenement buildings at Bryggen were owned by Hanseatic merchants. However, every tenement plot was rented and belonged either to members of the aristocracy or to ecclesiastical institutions.<sup>19</sup> This was still the situation at the end of the 18th century.<sup>20</sup> Systematic property studies covering the last 300 years have so far not been carried out.

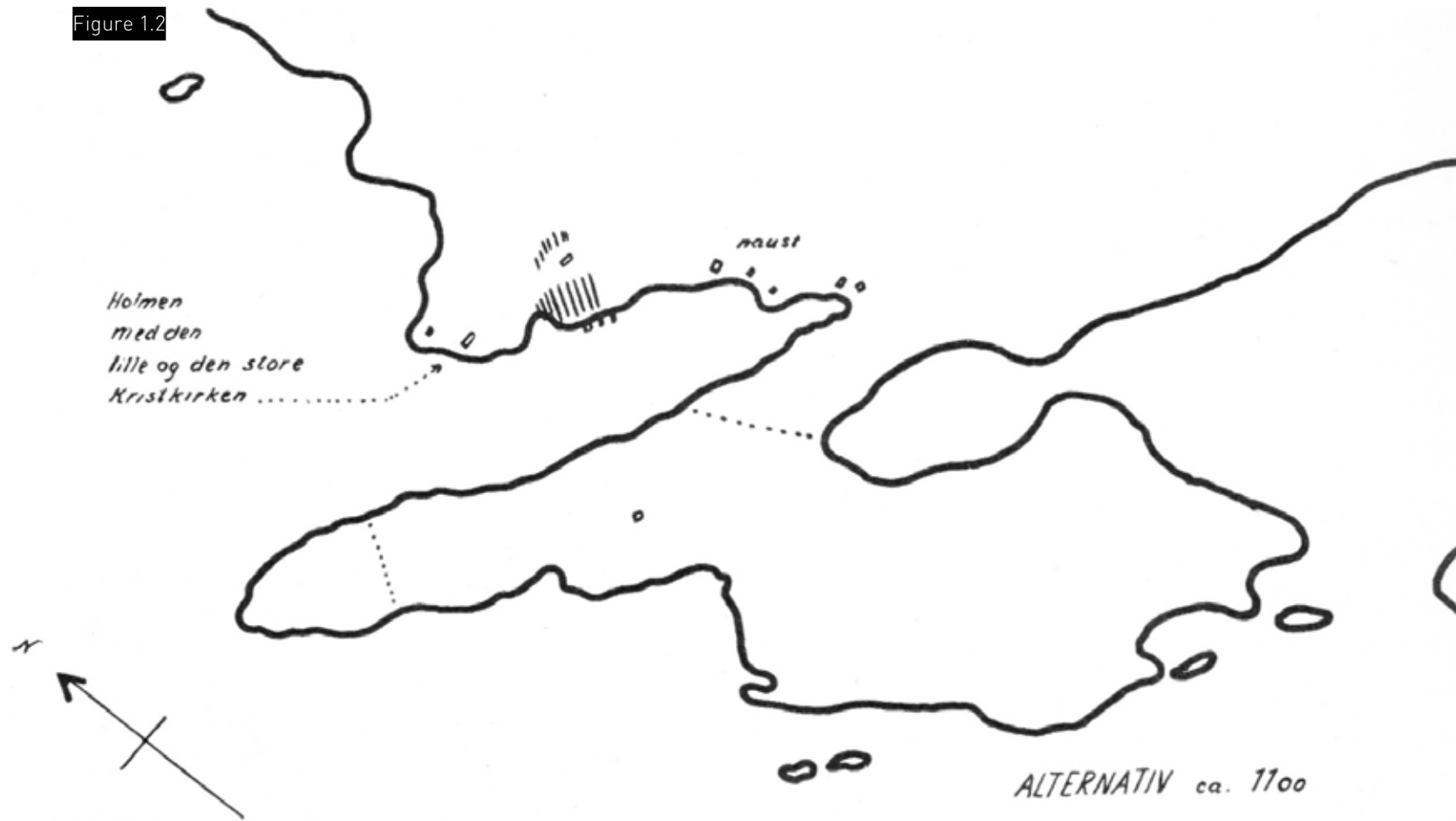
## THE BRYGGEN TENEMENTS

According to Koren Wiberg, the plot structure and the architectural features of the tenements remained unchanged through the centuries. Lorentzen contradicted this and argued that several changes to the plot structure had been made, and in the medieval period first and foremost after the major fires in 1248 and 1476. Lorentzen claimed that tenements were made both wider and higher after the fire in 1476. However, the written sources cannot provide any decisive evidence to support this hypothesis, and the archaeological investigations have since been able to shed considerable light on this question and have confirmed the idea of a plot structure that can be traced back to the earliest days of Bryggen.<sup>21</sup>

The archaeological investigations have also introduced crucial modifications to Koren Wiberg’s view. Prior to the investigations following the fire at Bryggen in 1955, there was no knowledge of the vast infillings in the harbour basin, which through the first few centuries alone had contributed to extending the tenements a long way – by at least 70 metres by 1332, and an extra 16-18 metres more by 1702.<sup>22</sup> With this in mind, ‘the historical longevity of the property boundaries has nothing to do with the length of the tenements, but with the width and the positioning of each tenement alongside the neighbouring property on both sides.

The medieval tenement at Bryggen prior to the Hanseatic takeover represented the basic entity of the settlement. It contained all functions needed in connection with the daily life of men, women and children. Families lived in the tenements, alongside visitors who rented rooms for a shorter period. We have very little knowledge of to what extent the tenement functioned as a collective entity, or if the inhabitants first and foremost were members of individual families. However, the building structure kept people close together and they had to share common spaces like the internal passageways and the wharf area. There were two kinds of tenements: the double tenement consisting of two parallel rows of buildings with an internal passageway between them, while a single tenement consisted of one row of buildings with a passageway along one side. Edvardsen described which tenements were double and which were single in the 17th century, what sign/symbol the tenements displayed, and expressed his opinions on the origins of the tenements’ names.<sup>23</sup>

Figure 1.2



Some of the tenement names at Bryggen appear in early writings such as the sagas, but most medieval names are found in deeds from the late 13th century and onwards. To local historians it has been a challenge to collate such names and sort them in terms of inner coherency both in time and space. This became a vital part of Koren Wiberg’s elucidation of Bryggen’s past, and it is also extensively discussed by Lorentzen, by Helle and by Ersland.<sup>24</sup> A toponymic study of tenement names was carried out by Brattegard (1943). What has fascinated both antiquarians and historians is the fact that the tenement names at Bryggen have continued in use into modern times. All the tenement names at Bryggen today are found in medieval sources.

This means that not only do we have the longevity of the spatial positioning of the plots, but the same applies to the tenement names too - and these aspects may well be related. Since the successive Hanseatic building owners rented the plots for several centuries and contracts for the plot rent were passed on without the interference of the plot owners when buildings changed hands, it was of vital importance to keep the old names in order to be able to demonstrate the whereabouts of a plot.<sup>25</sup> Keeping the names provided the tenements with historical continuity and legal validity especially after a devastating fire.

From the 16th century and up to the present-day, empirical data seems to confirm the longevity of the tenement structure, both in width and length. This is provided by deeds concerning some of the tenement plots in the 1560s. They furnish accurate measurements of the tenement plots in connection with fixing the yearly rent. Rented plots were a feature common to all the tenements at Bryggen, and since the rents from every tenement in the 1560s is found in a ledger from 1686, we know that

Figure 1.2 Bernt Lorentzen’s map of Bergen c. 1100 shows how he interpreted the settlement’s earliest stages. (Lorentzen 1952, p. 72).

the external dimensions for each tenement plot in the 1560s are consistent with the ones shown on maps from the 1880s.<sup>26</sup> However, the question of tenement longevity in the post-medieval period is also related to a series of modifications, because some tenements were removed or adjusted in situ, especially after the fire in 1702.

## BRYGGEN AND THE HANSEATIC KONTOR

The Town Law indicates that Bryggen was reserved for foreign trade, and this might explain why the Hanseatic merchants settled here from the 13th century onwards.<sup>27</sup> An organized community of Hanseatic merchants residing in Bergen was established by 1365 at the latest.<sup>28</sup> Further strengthening of this community’s administrative apparatus took place in the 1440s with the establishment of the post of Secretary.<sup>29</sup>

In the second half of the 15th century, the Secretary of the Kontor, Christian van Geren, wrote a chronicle, which at times gives some glimpses of life at Bryggen from a Hanseatic perspective. However, as a chronicler he does not demonstrate any narrative opinion on Bryggen or the Hanseatic privileged enclave residing there.<sup>30</sup> The authors of Bergens Fundas and Die Nortsche Saw (Den norske So) (c. 1580), along with Edvardsen, all give detailed information about how the Hanseatic privileged enclave and the Bryggen tenements were organized.<sup>31</sup> Edvardsen set a standard for describing Bryggen and the Hanseatic Kontor, a standard later followed by others, especially Ludvig Holberg (1737), who wrote the first History of Bergen to be published.<sup>32</sup>

We have to assume that once Hanseatic merchants had gained control of a tenement, they organized it to accommodate their needs. They lived within a so-called staven (firm, Norwegian stue) where either the owner or his representative was in charge of a number of foremen (Gesellen) and apprentices (Jungen). It was a non-family household where women and children had no place. A tenement accommodated several stavens, and the inhabitants regarded themselves as members both of the stue and also of the tenement as a collective. They prepared their meals together in a communal cooking-house, and in wintertime they also ate together in the communal Schöttstue. Their collective obligations were set down in by-laws.

The preserved tenements at Bryggen today is made up of buildings from the final part of the Hanseatic period in the 18th century, and the idea that the late Hanseatic tenement represents the medieval tenement is still prevalent. This can largely be ascribed to the writings of Koren Wiberg, especially in his book on Bergen and the Hansetics (1932).<sup>33</sup> There is not much recent research on the collective everyday life, and we know very little about the extent to which the Hanseatic takeover in the later medieval period represented a continuation of the ordinary medieval life at Bryggen, or involved a transformation to meet the needs of a mono-cultural trading society that adjusted the use of the tenements accordingly. The Hanseatic Kontor was dissolved in the 1760s. Its trade, along with a large part of its organizational framework, was adopted by Kjøpmannskontoret or Det Bergenske Kontor (Det norske Kontor), and established in 1754 by former members of the Hanseatic Kontor who had taken citizenship in Bergen.

## THE TOPOGRAPHICAL DEVELOPMENT OF BRYGGEN

An overview of Bryggen’s main topographical characteristics in the last part of the 13th century can be deduced from the Town Law (1276). In the paragraph describing the watchmen’s route, we learn that it was possible to walk along the harbour, traversing each wharf belonging to the corresponding tenement, and that the tenements were separated at certain intervals by broader public streets called allmenning (thoroughfares).<sup>34</sup> These ran at right angles to the waterfront and up towards Øvregaten, and were named Mariaallmenning, Buaallmenning, Breidaallmenning, Nikolaikirkeallmenning and Autaallmenning. The location of the Breidaallmenning mentioned in the Town Law is not known. Nikolaikirkeallmenning, on the other hand, is only mentioned this one time, and ran from the Church of St. Nicolas and down towards the harbour; it is puzzling that all later sources refer to this thoroughfare as Breidaallmenning. The Mariakirkeallmenning probably lead down to the harbour from St. Mary’s Church, and Buaallmenning was adjacent to the Bugården tenement.

Medieval Bryggen probably extended northwestwards to a point not far short of the southeastern edge of the royal castle - later the Bergenhus fortress - on the Holmen promontory. Late-medieval written sources indicate that the northernmost tenement was called Brynjolvsgård.







From 1476 until 1702, with the exception of the fire in 1527, which affected only a minor part of northern Bryggen, the area was not affected by a number of fires that raged at intervals elsewhere in the town. The fire in 1641 came close, right up to the southern edge of the Kontor, where the not very wide Autaaallmenning separated Bryggen from the rest of the town. As a precaution the southernmost Bryggen tenement, Rothmansgården, was torn down in 1643.<sup>45</sup>

In the 17th century, if not earlier, we find that the Hanseatic Kontor was letting out small plots of the five tenements that should have been left undeveloped. These plots were rented by other merchants at Bryggen, who then used them to put up extra storehouses.<sup>46</sup> In this way the original idea of firebreaks was disrupted. Perhaps this also explains the fatal consequences of the fire of 1702, which devastated the entire Bryggen area.

Apart from some stone buildings – some originating from the late medieval period, one built as late as 1666 – all of Bryggen was destroyed. Despite this, the rebuilding preserved the old tenement structure, with the exception of some relatively minor changes. Two tenements in the south, Vetrliden and Brødregård, were not re-erected, leaving Finnegården as the southernmost tenement. Holberg names 17 tenements at Bryggen after the 1702 fire.<sup>47</sup>

In 1865, the municipality of Bergen bought the Kappen tenement and demolished it to make way for a broader street running from the wharf towards Øvregaten and further up the hillside. The new thoroughfare was named Nikolaikirkeallmenning. Its creation made Bryggen more accessible to the public, and the wharf in front of the Bryggen tenements was made a public right-of-way. This coincided with the annulment of the Kontor’s privileges and the end of the traditional German services in St. Mary’s Church.

Except for the introduction of Nikolaikirkeallmenning in 1865, Bryggen hardly changed architecturally or morphologically from the rebuilding after the 1702 fire and up until the year 1899. However, this latter was a pivotal year in the history of Bryggen. A private consortium had bought a large area comprising the southern half of the quarter for the purpose of rebuilding the site. The project’s master plan introduced a grid by constructing two new streets crossing each other at right angles in the middle of the quarter. In this way four larger blocks were created that were eventually filled with buildings of various sizes and functions.

Apart from the decision to keep the facades within an architectural framework with connotations to Bryggen’s historical past and letting the new blocks keep the old tenement names, nothing was done to preserve the quarter’s former character. However, there was one anomaly: the Hanseatic Museum was left as a stump at the southernmost corner. The last building to be torn down was Kjøpmannsstuen (The Merchant’s House). This had been erected for the first time probably in the 1440s, and rebuilt after the fires in 1476 and 1702, to serve as the administrative building for the Kontor and to house the Kontor’s judicial assembly. It was not destroyed, but sold, and later re-erected in Matre in northern Hordaland County, where it is still standing.<sup>48</sup>

When concentrating on the numbers of tenements at Bryggen, there is a risk of overshadowing the driving force behind the creation of the building structure and its functionality. Both archaeological and written sources indicate that Bryggen expanded through a process of massive infillings into the harbour. The need for more building space and better wharfs to accommodate larger cargo vessels is probably the main reason for this development.

The Town Law states that property owners were responsible for keeping the wharf in front of their tenement in alignment with the neighbouring wharfs.<sup>49</sup> This indicates that the wharf was an integral part of the tenement, which in turn is confirmed by the deeds from the 1560s.<sup>50</sup> Late-medieval deeds state that each tenement was allowed to build only as far out into the harbour as their neighbours had done.<sup>51</sup> If so, further prolongation of the wharfs could only be carried out as a joint venture between neighbours. A good opportunity for such a collective undertaking would be the rebuilding process after major fires, which is also how Herteig interpreted the infilling process.<sup>52</sup>

Figure 1.4. Detail from panoramic overview of Bergen in c. 1740. Bryggen [32] is depicted with tenements and an open area along the lower side of Øvregaten. In the foreground is the Rozenkrantz Tower, and to the left the Church of St. Mary. (The original is kept at the Bergen University Museum).



Figure 1.4



Figure 1.5

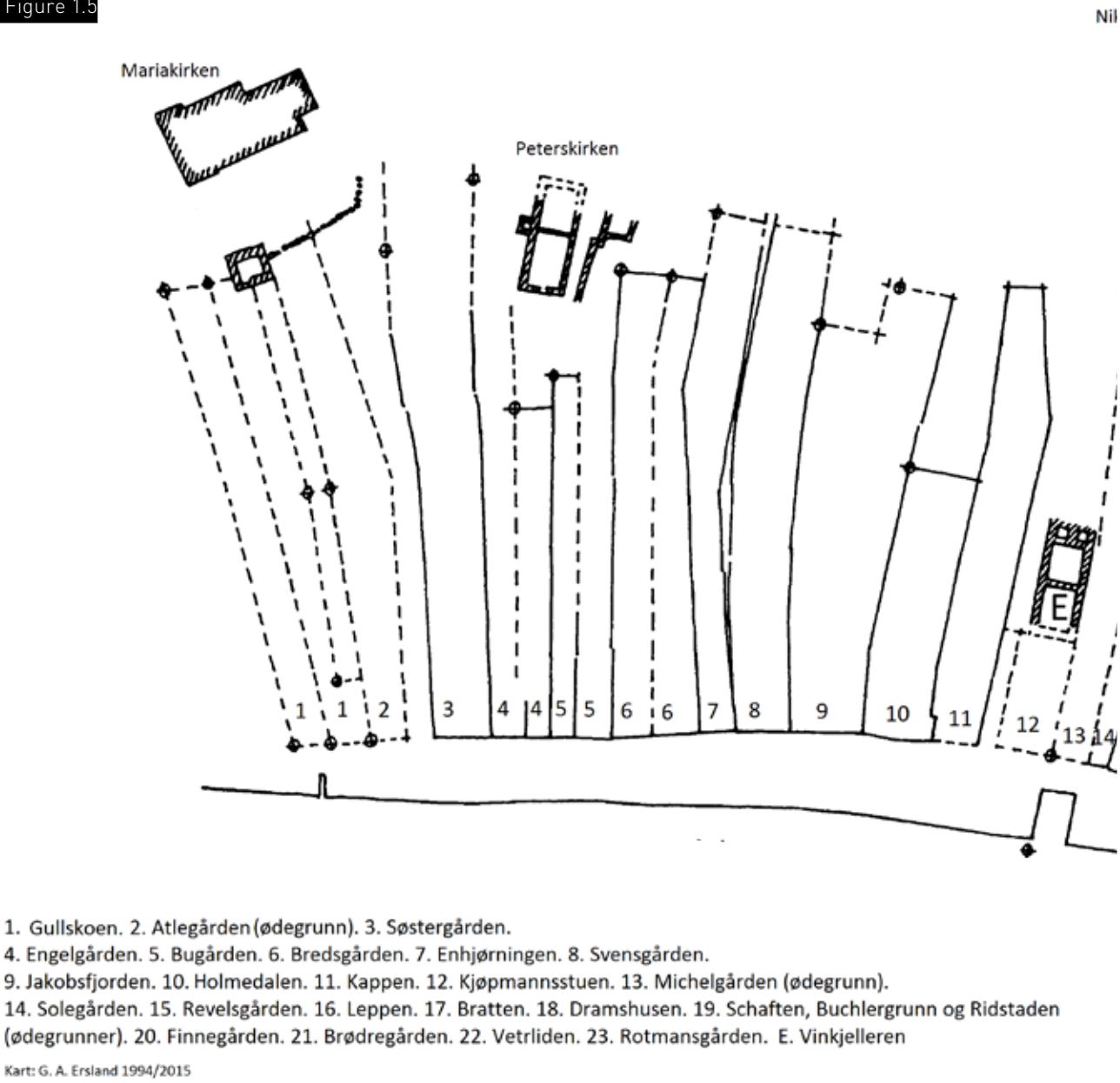
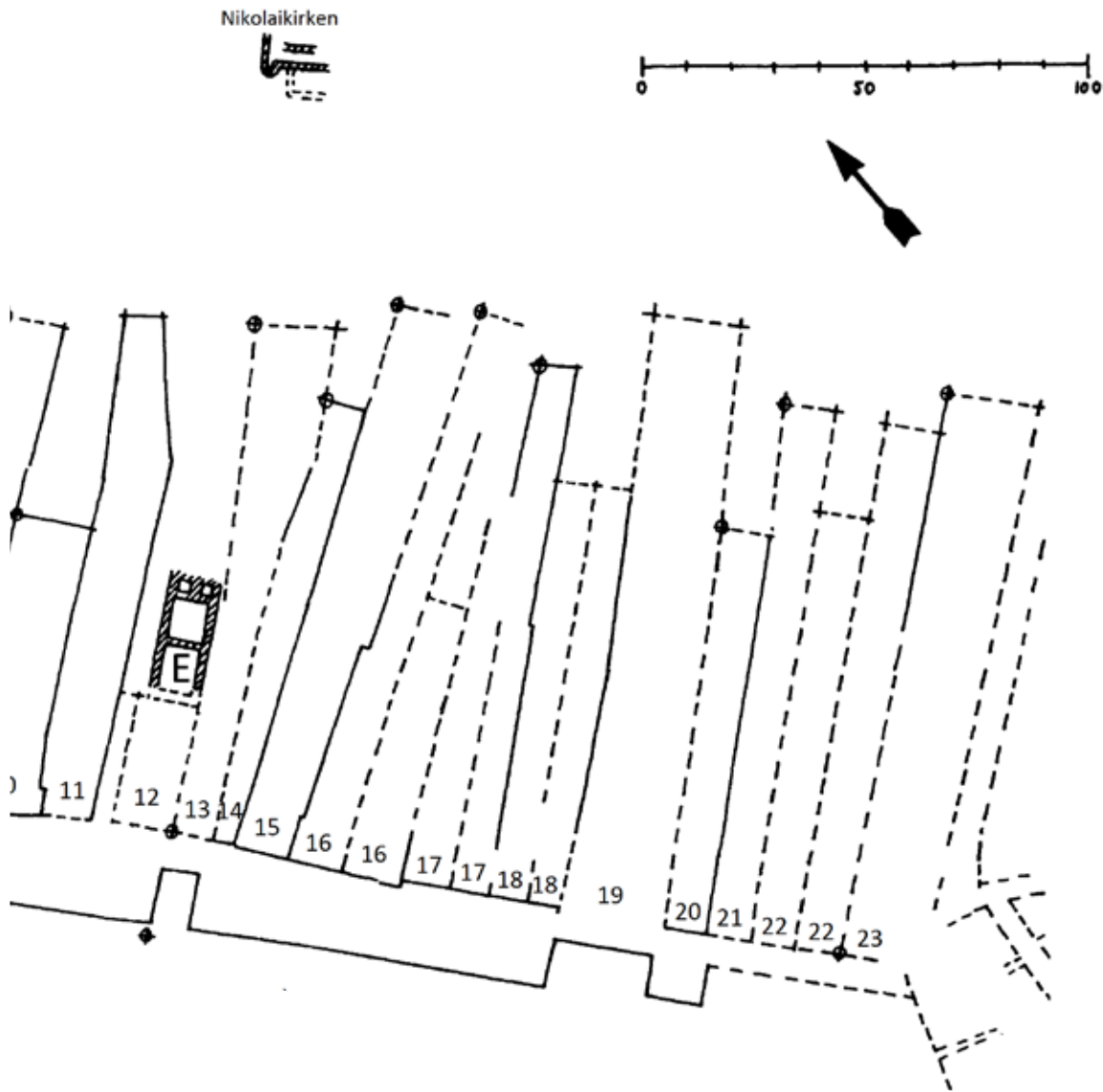
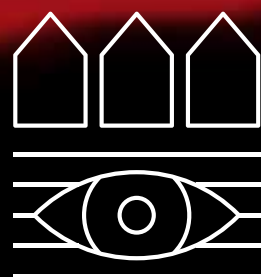


Figure 1.5. The annual plot rents for the plots at Bryggen, found in deeds from the 1560s and a ledger from 1686, can be used to calculate the length of each tenement plot at Bryggen in the 1560s. At that time the plots were measured from the quayfront. Numbers 2, 13 and 19 were left desolate (ødegrunn). The outline of each plot has been projected onto a detailed map from 1879/80, except for nos. 1 and 20-23, where minor changes to the plot structure had taken place following the rebuilding of the tenements after the major fire in 1702. Compare to figure 1. [Ersland 2011, p. 61-67].

Since the length of the tenements on maps from the 1880s - when measured from the front of the wharf - comply with the length given in deeds from the 1560s, this gives strong empirical support for the conclusion that the infillings had come to a halt at least by the mid-1500s, or probably after the rebuilding following the fire in 1476. Some minor adjustments were made after the fire in 1702. During the first decades after 1900 the wharf was widened to its present dimensions.





# 02

## WHAT THE GROUND REVEALED - THE ARCHAEOLOGICAL PERSPECTIVE

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Janicke Larsen  
Bergen City Museum



I love that man’s wife so much that fire seems cold! And I am that woman’s lover. These are the words of a man in love in Bergen in the late 12th century, and the words are carved on a wooden stick found by archaeologists some 800 years later. Archaeology gives us a wonderful perspective on everyday life in the Middle Ages, and on aspects of it that otherwise would have remained hidden from our eyes. Archaeological excavations have even produced supplementary written sources, since runic inscriptions have been found in abundance, telling about women’s fearfulness in connection with childbirth, of unhappy love, and botched trade and many other worries concerning ordinary people. Small traces of human activity can make a substantial contribution to our studies, and in this context I will highlight the importance of archaeology for understanding aspects such as Bergen’s medieval settlement structure, international trade and the lives of the townspeople – even some insights into the workings of the medieval mind will crop up along the way. I will focus on the High Medieval period, where the written sources are fewer in number and archaeology can relate unique stories of urban life.

## THE MAGNIFICENT ARCHAEOLOGICAL DEPOSITS

On archaeological sites, it is often only the durable non-organic material that is present, or at least overrepresented. At sites like Bryggen, however, both the non-organic and the delicate organic material are encountered, thanks to good preservation conditions. The organic material is a stunningly rich source of historical information, and one of the reasons that make Bryggen such a unique cultural resource is the vast volume of organic deposits laid down throughout the settlement’s almost thousand-year-long existence.

Over the centuries an urban community will accumulate a large amount of domestic, building and ‘industrial’ waste, interspersed with building remains, quayfront structures and infrastructure such as drains and wells. All of these remains of past human activity make up what we term the archaeological deposits. The primarily wooden settlement was very vulnerable to fire, and parts or all of it burned down many times over the centuries. After each fire, a new settlement was raised upon the ashes of the old. There are more than 10 major settlement levels at Bryggen, and due to this repeated process the archaeological deposits have accumulated to thicknesses exceeding 10 metres in places. Up till the end of the 1800s, the deposits remained



largely undisturbed by urban development and therefore extended under the entire Bryggen area – like a hidden treasure. Parts of this treasure were first uncovered when the southern part of Bryggen was torn down between 1900 and 1912, and more systematic excavations in recent times have steadily expanded our knowledge about Bergen’s archaeological history.

Owing to exceptional preservation conditions, generally speaking, organic materials constitute as much as 70% of the Bryggen deposits. When the process of decay begins

in a deposit, the delicate botanical and insect remains are the first to disappear, followed by the textiles, leather and others. Wooden artefacts can become unrecognizable, and even larger wooden constructions like buildings and quays will start to decay. Non-organic materials suffer on exposure to oxygen too; glass starts to disintegrate and metal rusts. Maintaining good preservation conditions is therefore crucial to the future of storytelling about Bryggen.

But good preservation conditions alone are not enough to ensure the information. Our archaeological history depends also on people foresighted enough to see the potential value of organic waste and to collect it during archaeological excavations in the same manner as jewellery and coins.

Figure 2.1 Bryggen prior to demolition and rebuilding of the southern half. Photo: K. Knudsen, The Department for Special Collections, The University Library of Bergen.



Figure 2.2

## DOCUMENTING AND EXCAVATING BRYGGEN - FROM MONUMENTS TO SCRAPS OF LEATHER

Bryggen in Bergen has been a UNESCO World Heritage Site since 1979. The site was inscribed pursuant to criterion iii) from the set of ten selection criteria for inscription on the World Heritage List. Criterion iii states 'Bryggen bears the traces of social organization and

illustrates the use of space in a quarter of Hanseatic merchants that dates back to the 14th century. It is a type of northern "fondaco", unequalled in the world, where the structures have remained within the cityscape and perpetuate the memory of one of the oldest large trading ports of Northern Europe'. Bryggen, with its thick, organic-rich archaeological deposits and its 62 protected wooden buildings, raised after the major fire in 1702, is a complex, fragile and unique cultural heritage. Soberingly, over three times that number of buildings existed a little over a century ago (Figure. 2.1).

Shortly after 1900, most of the southern half of wooden buildings at Bryggen was replaced by new brick buildings. During the demolition, local cultural-historian Johan C. Koren Wiberg (1870-1945) observed and documented the process and conducted surveys. He produced drawings of the wooden constructions that appeared in the archaeological deposits and collected artefacts.<sup>53</sup> Koren Wiberg was already interested in researching and documenting Bryggen, as he had inherited the Hanseatic Museum from his father in 1898. Koren Wiberg's private engagement was supported by the renowned archaeologist Håkon Shetelig at Bergen Museum and by the Municipality of Bergen.<sup>54</sup> At the time medieval archaeology was largely focused on investigating the remains of monumental buildings. This first generation of medieval archaeologists consisted mainly of architects and people interested in local history, and they formed the basis of Norwegian medieval archaeology in the mid-1800s. Archaeological deposits were not of paramount interest to these scholars, who concentrated rather on identifying and studying monumental buildings and clarifying their local topographical situation.<sup>55</sup> Koren Wiberg was therefore the first in Bergen to show interest in medieval buildings other than royal and ecclesiastical ones. In the years leading up to the mid-1900s, stratigraphy was still little used in the studies<sup>56</sup>, but Koren Wiberg was the first to grasp the significance of the firelayers that he encountered on his excavations, and he devised a method of firelayer chronology that is still an important component in dating archaeological remains in Bergen.<sup>57</sup>

Koren Wiberg's private and enthusiastic pursuit of medieval artefacts led to some public interest, but the real turning-point for the general public's archaeological awareness came as a result of a major fire at Bryggen in Bergen in 1955<sup>58</sup>, when 7,000 m<sup>2</sup> of the protected buildings burned down. The fire-ravaged area, now subject to heritage legislation, was therefore slated for archaeological investigation. At the outset it was assumed that the excavations would be completed in six months, but they lasted continuously for thirteen years, with a few follow-up excavations right up till 1979.

Thanks to Koren Wiberg, the presence of archaeological deposits and artefacts from the Middle Ages under the buildings was well known at the time of the excavations, but the methods used to investigate the archaeological deposits were pioneering. The leader was archaeologist Asbjørn E. Herteig, and he thought new and big. Under Herteig's leadership all artefacts were collected, including the smallest fragments of pottery, scraps of leather, bones and building remains - everything with traces of human influence. No distinction in treatment was made between gold and pottery shards. Documentation and excavation methods commonly used in prehistoric archaeology were applied to the archaeological deposits. Herteig documented all artefacts and all structures in two and three dimensions (x, y and partially z coordinates). As the excavations proceeded it became clear that the many historically known fires offered a particularly accurate means of dating the archaeological deposits - the firelayer chronology, a dating framework based on firelayers correlated with historical fires.

The excellent documentation and the many hundred thousand artefacts and building remains form an incredible basis for research on the medieval town of Bergen. The excavations after the fire in 1955 revolutionized medieval archaeology in Northern Europe, by both the methods employed and the sheer size of the endeavour. Never before had so many artefacts from daily life in the Middle Ages been collected, and they give us a rare chance to learn more about the lives of the medieval townspeople that lived in medieval Bergen. The material affords us valuable insights into daily life, throws additional light on some major historical events, and is fundamental in addressing questions such as how and where the earliest town nucleus arose, and how the settlement structure subsequently developed.<sup>59</sup>

## THE ARCHAEOLOGICAL MATERIAL

Although we obviously find points where history and archaeology overlap, we can as a rule say that while the written sources tell us about the few, the history of the vast majority of people who inhabited Bergen in the Middle Ages is told to us by archaeology.

The archaeological sources allow us to talk about the first town, and about continuity in the settlement structure in the Bryggen area. The traces of earliest

Figure 2.2 Sausage pins.  
Photo: G. Hansen, Universitetsmuseet i Bergen.





Figure 2.3

town structures are made of wood - completely at the mercy of good preservation conditions. Buildings, clothes, shoes, foodstuffs, plates, pieces of boats, and fishing gear are also mostly made of organic materials, and these remains constitute the bulk of the archaeological finds. Only about 20 % of the archaeological finds consist of non-perishable materials such as stone and ceramics.

When we have both organic and non-organic archaeological material in the same context, we can obtain a much more comprehensive picture of the Middle Ages. And when we add the statements and messages written on rune sticks, we can get a glimpse of hundreds of small, personal - and yet incomplete - stories, in addition to the larger storylines of politics, urban development and trade.

## AN INTERNATIONAL TOWN ARISES

The archaeological sources show that from the beginning of the 1100s the town's development started to accelerate in earnest. This is visible in the strong increase in the volume of archaeological material. Throughout the 12th century the archaeological sources now bear witness to a lively town with Norwegian and foreign merchants, thrifty women who kept inns with beer and sausages for sale (Figure 2.2), young children playing in the tenements, and itinerant artisans who came to town and sold things such as fancy leather shoes with silk embroideries, antler combs and other accessories to the townspeople (Figure 2.3).

The settlement burned down time and again throughout the Middle Ages. Eight conflagrations and a couple of partial fires have been identified in archaeological and written sources.<sup>60</sup> As the town was almost entirely built of wood it burnt very well; we hear from the written sources about how 'everything burned'.<sup>61</sup> The archaeological sources show that after each fire the town was rapidly rebuilt. During the town's first centuries, the tenements at Bryggen advanced steadily into the harbour bay (called Vågen) after each fire; the need for more building land and deeper water along the quays was an urgent matter in the busiest trading centre of the North Atlantic. The tenements were extended into Vågen by up to 35 metres in one go (Figure 2.4).<sup>62</sup> Boundaries between the tenements were, however, strictly maintained, as were the locations of streets and thoroughfares.

Figure 2.3 Fancy shoes in various shapes and sizes, toys, bone combs, and decorated bone hairpins.  
Photo: G. Hansen, Universitetsmuseet i Bergen.

## FACES OF GRIMSTON - A TALE TOLD BY POTTERY SHARDS

Ceramic is a useful archaeological material for dating purposes and is an excellent source of information about trade in the Middle Ages. As far as we know, there was no domestic pottery production during the Middle Ages whatsoever - apparently it was all imported from various regions in Europe. However, we do not know if it came to Bergen as a commodity in its own right or as containers for other merchandise, nor do we know how the pottery was distributed when it reached the town. Pottery is particularly important because it tells a different story of trade than the written sources do; the written sources hardly mention pottery, but the archaeological material teaches us that it was imported to Bergen in massive quantities.

Pottery does not disintegrate easily and will survive even under very poor preservation conditions, and is therefore an important and classical finds type with both chronological and typological characteristics for determining provenience and dating. Although the pottery is normally highly fragmented and worn, it is more precious than gold to the archaeologist.

The pottery I will emphasize in this connection is Grimston Ware, produced in the parish of Grimston in Norfolk, East Anglia, situated around 8 km from King's Lynn and 64 km from Norwich. Today, almost 2,000 people reside in Grimston, but in the Middle Ages the parish only had between 100 and 200 inhabitants, concentrated in the village of the same name, and the nearby hamlet of Pott Row.<sup>63</sup>

In the 13th century, Grimston appears to have been the only manufacturer of glazed pottery in Norfolk.<sup>64</sup> The most important nearby market for Grimston Ware was Norwich, one of England's largest and richest cities, but the pottery can be found all over England, and in large amounts in East Anglia. However, most of the production was exported, being sent to the port of King's Lynn for shipping to numerous destinations; many of these were in Scandinavia, and Bergen appears to have been the largest importer of them all (although, as mentioned previously, we cannot say that the pottery per se was a trade commodity). Bryggen has so far yielded more than 4,000 pieces of face jugs from Grimston, and most of these are in contexts dated from 1200 to the 1300s. This is the largest group of pottery from this period found in Bergen.<sup>65</sup> It actually seems like it has been exported as much pottery to Bergen during this period as was sold locally in the Grimston area in the same period.





Figure 2.4

The connection between Grimston and Bergen seems to remain strong until the Hanseatic merchants took control of Bergen’s commerce from the mid-1300s and Bergen’s trade became increasingly focused on northern Continental Europe rather than England.<sup>66</sup> After this, production in Grimston apparently went into decline and fewer products found their way to Bergen; nevertheless, we continue to find Grimston pottery in Bergen throughout the Middle Ages and even a bit longer.

There is no mention of how the green-glazed, decorated pots were used, or how much you had to pay for them, no record of the production or the producer, nor of the buyer/user. This may indicate that the pottery represented packaging rather an export/import article in its own right.

Figure 2.4. Quay structures of wood.  
Photo: Bryggens Museum.

Wine, oil, spices and other valuable goods could well have been exported in Grimston jars and jugs, but only the contents of the vessels would have been subject to duties.

We can tell a lot based on only one silent archaeological find category, but it is more exiting when you can relate these finds to a larger context - to a deposit containing other contemporary artefacts, to a building - or to a person.

### VOICES FROM THE PAST

Now we have seen examples of how the archaeological material can provide information about things such as urban development, trade and goods. But what about the individual? One particular archaeological find category surpasses all others for this purpose: the runic inscriptions. They can bring the international and urban perspective to a new level, complementing the perspective already presented. Some of the runic

inscriptions can be related to persons, both named (and historically known in some cases) and unnamed. Other relates to everyday incidents, to European poetry or even trade letters written in a formal tone.

The runic material is really delicate, and is in a way both a historical written source and an archaeological artefact - a sort of hybrid source. What makes them special in comparison with other contemporary sources is that they give voice to townspeople in their everyday language, not much different from our SMSs, as well as more formal language like the ones we know from other written sources. The material indicates that people of different status could write and/or read runic inscriptions. Examples of mundane inscriptions include the following: ‘Playing high with dice can lead to many things...’, ‘Ingebjørg loved me when I was in Stavanger’, and ‘Love me, I love you, Gunnhild! Kiss me. I know you.’

Runic inscriptions provide us with unique and intriguing insights into the medieval mind and general daily life in the Middle Ages, and the largest collection of medieval runic inscriptions in the world is from Bryggen; most of them are carved on simple wooden sticks. Every one of the runic inscriptions is by itself a source of information about the medieval society, often describing people, situations or relations not found elsewhere. Among the more than 600 inscriptions found at Bryggen, we find trade letters, ownership marks (name tags), receipts, magical spells, religious inscriptions, poetry and literature references in Old Norse or Latin, secret messages, lewd messages, drunken and incomprehensible messages<sup>67</sup>, like the one that reads ‘Gyða segir at þú gakk heim’ (Gyda says you are to go home) (Figure 2.5). There are inscriptions on two sides of the stick, but the one on the other side is illegible<sup>68</sup> and clearly written by a different person, interpreted as an attempt to answer Gyda. Who has answered, and why is the answer illegible...? This stick raises a lot of obvious questions. Who is Gyda? Who is supposed to go home - a child or a man, and from where? Why is Gyda bothering to carve this message instead of going to fetch this person? Or was it delivered by messenger? Why could the message not be conveyed orally?

- a. gya:sæhir:atþu:kakhæim
- b. þansak:abakist:rþis

Perhaps the greatest importance of this stick, and others like it, for us is because of the questions they allow us to ask about medieval everyday life; they allow us to wonder! It is evocative. Some of the other sticks tell us about domestic affairs already known to us, but some invite us to review established truths, like the rune stick carved by King Sverre’s oldest son, Sigurd Lavard (Lord) [c. 1175-1200]. This is a totally unique document. We know Sigurd from Sverre’s Saga, where he is twice referred to as a weak coward.<sup>69</sup> Sverre’s Saga was partly written while King Sverre was still alive, so it could be the king’s own opinion that is expressed. Can the rune stick give us a different impression of the king’s maligned son?

- There are runes on all four sides, and they say:
- a. Sigurd Lavard sends God’s and his own greetings. The king would like your Skeid/Smid. For.
  - b. Weapons on.....spears from the 18 ells of iron that I sent you with Johan
  - c. Ore. Now I request of you that you will cooperate in this matter.
  - d. If you do this now, according to my will, then in return you shall have our friendship now and forever.

The interpretation of the text is clear, except for the word Skeid/Smip in line a. If it reads skip - interpreted as «Skeið», meaning ‘longship of the largest type’, this means that Sigurd was a trusted man. If, however, it says smip «Smið», meaning ‘the product’ - a craftsman’s product - this indicates a role that would have been unworthy of an heir to the throne. Note that what is decisive for the interpretation is the disputed presence of one very short oblique stroke - a scratch a mere millimetre in length - that may or may not have been part of one of the letters. Its presence or absence completely changes the meaning. Is it there - or is it not? This is what the inspection of runic inscriptions can sometimes boil down to. And it reinforces the importance of continued good preservation conditions, or else who can say how many buried runic inscriptions will become ambiguous, and eventually unintelligible.

Some of the rune sticks contain references to a cultural or religious context and part of a European tradition. One such is a small stick where five names appear: Dionysos, Johannes, Serapion, Malchus and Maximianus.<sup>70</sup> The stick is dated to the latter half of the 13th century (later than the firelayer correlated to the historical fire in 1248). These names relate to the well-known medieval legend of the seven sleepers.<sup>71</sup> We know this legend from several



sources, and it takes place in Ephesos, where seven Christian men sought refuge in a cave on the mountain Celion, to escape the Emperor Decius. The emperor had the cave walled up. When the cave was opened 300 years later, the seven men were found sleeping. They awoke for a moment, professed their faith to the bishop, and died peacefully.<sup>72</sup> The legend is best known from Jacobus de Voragine's *Legenda Aurea* from c. 1260, but the runic inscription from Bergen is probably older, and is based on an older tradition.

This rune stick from Bryggen is shaped like an amulet, and there are several examples where the seven names have been used in magical ailment-treatment, especially for insomnia, but also for fever and malaria. Perhaps this amulet had a similar use.<sup>73</sup>

The runic inscriptions tell of a diverse society, of everyday worries and the influence of central European culture. The closeness to the people before us - they give words to all those silent objects.

CONCLUDING REMARKS

When studying a medieval society, archaeology becomes a strong source of information. Particularly good and complementary perspectives emerge when archaeological artefacts are studied in tandem with written sources. We are able to do this today thanks to good preservation conditions and good archaeological methods. Perhaps it was Gyda's man who had to come home from the city's wine cellar where he had been sitting and drinking beer poured from a Grimston-ware face jug? A complex material opens for questions like this - or at least it gives us some footholds to put a human complexion on a period many centuries removed. Because that is what archaeology is about: the study of material culture to say something about the non-physical culture, and the individual people.

If all the organic material were to disappear from the deposits, our basis for understanding the Middle Ages would be drastically reduced, and the medieval people would recede still further from us. Rune sticks, for example, are fragile, and even a small deterioration in environmental conditions in the deposits can cause the runes to disappear, rendering the inscriptions forever

Figure 2.5 'Gyda says you are to go home'. Drawing: T. Sponga, © Riksantikvaren.

impossible to read. By examining the rune sticks, we gain insight both into the vulnerability in the material, but also into the historic potential every one of these sticks has. Without the organic material, the ceramic artefacts would lack much of their contemporary context.

A lot of sources can tell us about medieval life, but none of them can tell stories quite like the hybrid runic inscriptions. Good preservation conditions in the deposits under Bryggen are essential to the archaeological material. And the archaeological material is essential when drawing a complete picture of the history of Bergen - and Norway!



Figure 2.5



# 03

## MANAGEMENT HISTORY

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Figure 3.1



On April 23th 1927 Bryggen was listed as an historical monument pursuant to the Act on the Preservation of Buildings of December 3th 1920 section 2, second paragraph. At the time of listing, Bryggen was only half the size it had been just a few decades earlier. Unfortunately, the listing is not underpinned by stated reasons, and the registration contains only the names of the individual buildings and their owners. In this period listing was being carried out at a great rate, and in order to speed up the process, the Ministry of Church and Education set up 'Den antikvariske bygningsnemnd' (The Antiquarian Buildings Commission). This committee's reports were printed in 'Foreningen til Norske Fortidsmindesmærkers Bevaring' (The Society for the Preservation of Norwegian Ancient Monuments) and the society's 1927 year book contains the following about Bryggen: 'On the other hand, it should be emphasized that there are buildings on Tyskerbryggen that remarkably have not only retained their building function but also to a certain extent their medieval character, thanks to the respect that the Hanseatic showed for old Norwegian building traditions'.<sup>74</sup>

The buildings at Bryggen were heavily damaged on 20 April 1944. The Dutch ammunition ship 'Voorbode', which had been tied up at the quay between Bryggen and the fortress of Bergenhus, caught fire, and 120 tons of munitions exploded with incredible violence at 08.39 hours.<sup>75</sup> Several hundred houses were totally or partially destroyed and 158 people lost their lives. All the roofs of the historic buildings at Bryggen were blown off and since then the remains of these roofs and a considerable amount of other rubbish have been clogging up the narrow gaps ('eavesdrops') between the buildings.

On 4 July 1955 fire destroyed large parts of the listed buildings on Bryggen and exposed a large area with thick cultural deposits. The decision was taken to excavate the area. A. E. Herteig was appointed as head of the excavation project, and the first and largest survey of a medieval township in Norway began using innovative

Figure 3.1 Bryggen around 1900, with counterbalanced lifting booms along the quay.  
Photo: unknown. © K.Knudsen, Bergen.



methods of field documentation, finds recording in databases, and other methods such as 14C-datings and scientific sampling. Alongside the archaeological fieldwork, Herteig also started restoration work on the remaining buildings on Bryggen and in November 1962 Stiftelsen Bryggen (The Bryggen Foundation) was set up by Bryggens Venner (The Friends of Bryggen).<sup>76</sup>

In 1955 Bryggen was still known as Tyskerbryggen (The German Wharf). Following the excavations, both the understanding and the management of Bryggen changed, as Herteig was able to show that the structure was Norwegian, not German. The excavations were also highly significant for the development of medieval archaeology and the management of medieval townships in Norway.

Figure 3.2 Bryggen - artist's impression of the Voorbode explosion on April 20th 1944. The photo inserts show the damage done to the historic buildings' roofs.  
Drawing: T. Sponga, © Riksantikvaren.  
Photo: Unknown. In BT's photo archive.



Figure 3.3 Bryggen's northern part goes up in flames in 1955 . Photo in Riksantikvaren's archive.





Figure 3.4:1



Figure 3.4:2

## BRYGGEN: WORLD HERITAGE SITE

In the spring of 1978 the Western Norway office of Riksantikvaren (The Directorate for Cultural Heritage) proposed that Bryggen should be inscribed as a World Heritage site, because Bryggen represents the remains of a Hanseatic privileged enclave and an example of urban development on the periphery of Europe and the remnants of old North European urban building traditions. When ICOMOS later approved inscription on the World Heritage List, this was backed up by the arguments in the application, but the greatest emphasis was on the former presence of the Hanseatic League. At a meeting of UNESCO in Egypt in 1979, Bryggen in Bergen was inscribed as number 59 on the World Heritage List under criterion 5a ii: 'to bear a unique or at least an exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared'.

The Bryggen World Heritage site (Bryggen WHS) has been subject to assessment twice, in 1993 and 2000. Both times a recommendation was made to extend the world heritage inscription to encompass criteria 5a iv ('to be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates significant stages in human history') and 5a v ('to be an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture, or human interaction with the environment especially

when it has become vulnerable under the impact of irreversible change'), and to formalize Finnegården as part of the Bryggen World Heritage site (Bryggen WHS). In the report from 2000 a recommendation was made to further extend Bryggen to include Mariakirken (St Mary's Church) and to follow this up with a re-evaluation of the whole of the medieval heart of the city of Bergen, i.e. the area from the cathedral to Bergenhus/Sverresborg.<sup>77</sup> This has not been followed up but Finnegården is treated by the national administration as though it were part of the World Heritage site (Bryggen WHS).

In the meantime, in 2006 Bergen municipality included the quays and Bryggen in the Vågen zoning plan and zoned a large area around Bryggen for special preservation. The above comments indicate that the nomination may need to be extended. On the other hand, it is good to see that later evaluations show that restoration work is well underway and that the work to reduce the loss of groundwater is producing good results.

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Figure 3.4:1-2 Demonstration supporting demolition of Bryggen (1). Today, the area has around 1.2 million visitors annually (2).  
 Photo 3.4:1 Photo: Unknown. Riksantikvaren.  
 Fig.3.4:2 Photo: A. Kjersheim, Riksantikvaren.



Figure 3.5

## MANAGEMENT

Cultural heritage protection is an integral part of environmental protection work in Norway, and Riksantikvaren, as the Directorate for Cultural Heritage, comes under the Ministry of Climate and Environment. Fundamental principles in today's cultural heritage management are 'the precautionary principle' and 'the polluter pays' principle and sustainable management of cultural heritage as a non-renewable resource. The principle of sustainability was introduced by the Brundtland commission: 'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs'.<sup>78</sup> The principle of in situ preservation is taken up in parliamentary white paper no. 16 (2004-2005) *Leve med kulturminner* (Living with cultural heritage)<sup>79</sup> and parliamentary white paper 35 (2012-2013) *Fremtid med fotfeste* (A future firmly anchored in the past) where archaeological cultural heritage is classified as a non-renewable resource.<sup>80</sup> It further states that the archaeological deposits in medieval towns are our subterranean archive and that excavations

must be restricted. Some of these principles have been considered further in parliamentary propositions in the period 2005-2013.

The 'in situ' principle is therefore important in the current management of archaeological cultural heritage. In sub-aim 1 in the 'Strategic plan for the management of archaeological cultural heritage and cultural environments 2011-2020' it is stated that 'The safeguarding of archaeological cultural heritage and cultural environment is based on a good database, uniform criteria and responsible methods' and 'Knowledge about the condition of cultural heritage and cultural environments, how these change and the reasons for this are vital for drawing up good policies and management. Environmental monitoring (MOV) provides results through systematic, long-term data collection. This provides a basis for deciding what types of measures should be implemented if cultural heritage is threatened by damage or destruction. Though systematic monitoring it is possible to find out what effect the measures are having and adjust these where necessary'.<sup>81</sup>

Since 1912 Riksantikvaren has had specific responsibility for the management of selected cultural heritage from the Middle Ages which is enshrined in the current Cultural Heritage Act and the 'Forskrift om faglig ansvarsfordeling mv. etter kulturminneloven' (Regulations concerning the allocation of scientific responsibility etc. in accordance

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Figure 3.5 Documentation of archaeological deposits and constructions in a section at Bryggen.  
 Photo: Universitetsmuseet i Bergen, UiB.



Figure 3.6



Condition class.  
CC-1  
CC-2  
CC-3

with the Cultural Heritage Act). This applies to eight selected towns and cities from the Middle Ages. The archaeological cultural heritage at Bryggen is part of the automatically protected, scheduled cultural heritage object ‘the medieval city of Bergen’ and is managed on the same lines as the rest of the city and the seven other medieval towns and cities. There are still 155,000 m3 of archaeological deposits on Bryggen today, which make it the largest remaining cohesive area of such deposits in our medieval towns and cities that has not been disturbed by major modern works. Bryggen, with its archaeological cultural heritage, is included in and managed as part of Riksantikvaren’s preservation programme for World Heritage and is organized as ‘Prosjekt Bryggen’ (Project Bryggen). Bryggen’s intact historic landscape is today managed as a cultural environment primarily through the Planning and Building Act and the current zoning plan for Vågen, Kaiene and Bryggen.

Finance & subsidies

Up until 1999 funding for the restoration work on Bryggen was channelled directly to Stiftelsen Bryggen. The initial annual amount provided for this work was NOK 200,000. Since 2001, when ‘Prosjekt Bryggen’ began, the funding has gradually increased and is now given as a subsidy to Hordaland County Council, initially comprising a couple of million Norwegian kroner and now amounting to NOK 15-18 million annually. The subsidy is for works that affect the whole of the complex cultural heritage, both above and below ground.

Condition surveys

All the historic buildings, including the foundations, have undergone a condition survey in accordance with European Standard CEN- EN 16096:2012, Conservation of cultural property, Condition survey and report of built cultural heritage.<sup>82</sup> In this assessment, 27 buildings achieved condition grade 3 which indicates that the building is in a poor state, while seven buildings achieved grade 2 which indicates a continued need for repairs, but a rather less precarious state, while 28 buildings

achieved grade 1, simply requiring ordinary maintenance. There are a number of reasons why the buildings are in relatively poor condition. Use of the buildings has changed since Bryggen’s heyday, and for a while the buildings had less economic value for their owners. Much of the decay is therefore due to the fact that many of the repairs following the explosion in 1944 are characterized by being of a temporary nature. And groundwater levels that are considerably lower than before also lead to subsidence damage and further decay.

ORGANIZATION

Riksantikvaren manages ‘Prosjekt Bryggen’ as part of Riksantikvaren’s preservation programme for World Heritage, which is one of ten preservation programmes. Riksantikvaren allocates resources and subsidies for restoration work to Hordaland County Council, which then allocates subsidies to the property owners. The municipal Cultural Heritage Management Office and Riksantikvaren manage other parts of the project. The property owners carry out the restoration works. In 1996 a cooperative working group was set up comprising representatives from the administration, the owners, and other interested parties. The aim of the group was dialogue, discussion of issues and problems of common interest and sharing information. The operative steering group (OPS) with representatives from Riksantikvaren, Hordaland County Council (through the county conservation officer) and Bergen municipality (through the Cultural Heritage Management Office) was set up on 27 March 2007. The group is led by representatives from Riksantikvaren. The aim is to clarify roles and the division of responsibilities in ‘Prosjekt Bryggen’, financial management, contributing to the effective implementation of measures in the project, and coordinating the administration. The operative steering group also lays down the repair principles for work being done on Bryggen. Tasks must be tackled using ‘best practice’ and in accordance with relevant acts, directives and annual parliamentary propositions, and work-commission orders from Riksantikvaren.

The management plan

‘The management plan shall be a tool for ensuring the best possible protection of the Bryggen Wold Heritage site so that the cultural resources can be handed down to succeeding generations as intact as possible’ (Hordaland fylkeskommune, 2005).<sup>83</sup> The management plan has been drawn up by Hordaland

Figure 3.6 Conditions survey of buildings at Bryggen in 2014 in accordance with EN16096:2012 Conservation of cultural property - Condition survey and report of built cultural heritage. Map: Riksantikvaren.





Figure 3.7

County Council in close cooperation with Riksantikvaren, the municipal Cultural Heritage Management Office, and the property owners. The plan builds on a shared understanding of the values that reside in the Bryggen WHS and of how these should be managed. The plan is to be revised every three years in order to include new projects or make necessary changes.

### Restoration principles - the wooden foundations

In the middle of the 1990s there was a shift in restoration principles away from the use of modern materials in foundations. A method of restoration was introduced whereby traditional methods and materials were used as far as possible. In this way both the techniques and access to materials are retained. This also meant that the method used for the new foundations of newly-restored buildings moved away from pile and concrete footings and went back to using traditional, cross-laid rafts of horizontal timbers to replace the rotten timbers. These rafts were to contain at least three courses of logs, and nowadays work is going on where necessary to replace

the timber foundations all the way down to the firelayer deriving from the 1702 fire, where deposits of ash, charcoal, broken bricks/tiles, gravel and stones make up an excellent impermeable layer. In those places where the firelayer is missing, attempts are being made to recreate the stratigraphic conditions.

### ACQUIRING KNOWLEDGE

Current knowledge has been fundamental both in connection with the archaeological excavations at Bryggen and in relation to preserving the remaining archaeological deposits and historic buildings. The period between the fire in 1955 and up until 1979 was characterized by the major excavation works on the site of the fire at Bryggen.<sup>84</sup>

Figure 3.7 Building renovation works at Bryggen. Marius Røbech (foreground) and Sondre Andersen from the Bryggen Foundation are constructing a new timber foundation for a building using traditional methods. Photo: E. Jensen, Stiftelsen Bryggen.

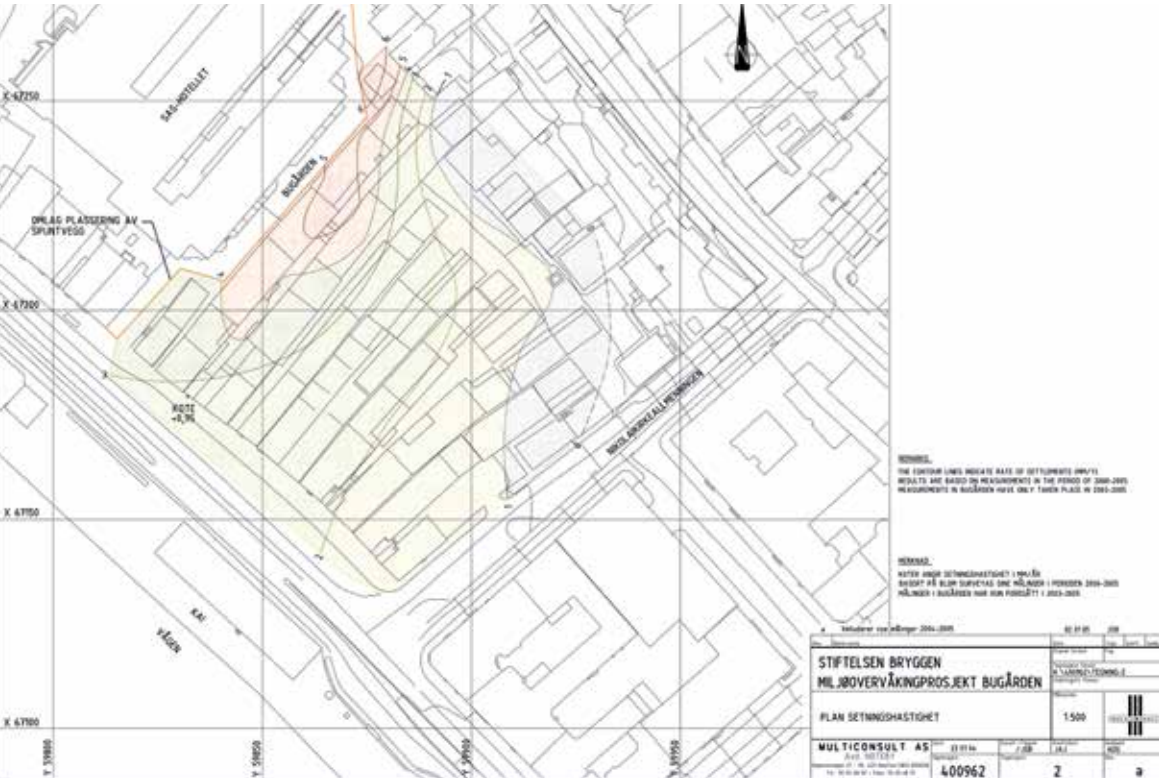


Figure 3.8

As mentioned above, these excavations' findings brought benefits for the remaining buildings. Since the 1960s, preservation and restoration of the buildings themselves have been prioritized. A natural result of this has been that the archaeological deposits under the buildings have remained relatively untouched.

Knowledge of preservation and monitoring of the archaeological deposits is a relatively new science that emerged in Britain in the middle of the 1990s as 'environmental monitoring'. Prior to 2000, small monitoring projects were implemented in Tønsberg and Trondheim. Monitoring work at Bryggen began in 2000 with the installation of two monitoring wells in connection with the restoration work in building 5e. At the same time a separate project started on 'Safeguarding historic waterfront sites - Bryggen in Bergen'.<sup>85</sup> One of the results from this was a greater emphasis on environmental monitoring. More monitoring wells were installed, and it became apparent that the area bordering the modern

hotel building showed very fluctuating values. Early on in the process it was agreed that two concepts within the field of in situ preservation needed to be taken into account: the state of preservation, which describes the archaeological deposits' current condition, and the preservation conditions, which describe the environmental conditions in which the deposits lie. Armed with data on these two factors, the goal is to be able to evaluate rates of decay in the archaeological deposits and to assess the threats to which the deposits may be exposed.

### Environmental monitoring at Bryggen until 2010

Observed damage to buildings meant that in 1999 subsidence measurements began on Bryggen. In order to find out the causes of the subsidence, the first two monitoring wells were sunk as described above, in 2001. Detailed descriptions of the archaeological context and geochemical content in drilling and water tests were reported. During 2002 the first conclusions from the subsidence measurements were ready. Subsidence of up to 8mm a year in the northeast corner of the Bryggen WHS was directly related to changes in the groundwater level. Since 1979 the groundwater in the most exposed

Figure 3.8 First map showing amount of subsidence at Bryggen, 2002. Map: Stiftelsen Bryggen/updated 2005, Noteby AS 2004.



Figure 3.9



parts of Bryggen had fallen by up to 2.6 m.<sup>86</sup> As a result of this Riksantikvaren began intensive monitoring of the groundwater, primarily using data from a total of 35 monitoring wells sunk up until 2010. In 2007 a hole was dug in the most exposed area in order to install monitoring equipment and modern samples of wood were inserted above the ground water level (unsaturated zone). The hole showed undisturbed organic cultural deposits from the Middle Ages beneath a stone cellar. In 2010 the hole was re-opened and samples of fresh wood were taken. Additional oxygen monitors were installed. One important aim of the monitoring is to find out the speed of deterioration in the archaeological deposits.

In 2010 it was concluded that about 30m3 organic material was disappearing each year due to the decay of the cultural deposits in the most exposed zone.<sup>87</sup> This figure, together with the subsidence measurements for the buildings in Bredsgården, was reported to the then Ministry of the Environment.

## KNOWLEDGE TRANSFER

Knowledge acquired at Bryggen is transferred directly to the management of similar cultural heritage properties in Norway. In the period 2005-2007 the Pele project was carried out as a result of parliamentary white papers 16: Leve med kulturminner.<sup>88</sup> The aim was to investigate whether there were foundation engineering methods that avoided damaging archaeological deposits with a high organic material content, while at the same time enabling urban development. The methods for establishing the state of preservation and the preservation conditions were those that were developed as part of the environmental monitoring programme on Bryggen.

Figure 3.9 Piles drilled through archaeological deposits in Tønsberg. Photo: J. Rytter, Riksantikvaren.

Briefly the project involved collecting documentation about the state and conditions in archaeological deposits close to the piles. The investigations showed no sign of damage close to the drilled piles. Following this project a measure was introduced with conditions whereby permission must be obtained for piling in certain types of building projects. Piling is not suitable for Bryggen. In the period 2005-2014 environmental monitoring was introduced in the majority of mediaeval towns and cities in Norway and also for other categories of cultural heritage. In addition a Norwegian standard for environmental monitoring of cultural deposits has been drawn up in NS 9451:2009 (also available in English)<sup>89</sup> and guidelines in SINTEF Byggforskserien 721.305 Bygging på kulturlag i middelalderbyene (Building on cultural deposits in medieval towns and cities).<sup>90</sup>

Riksantikvaren has also made the work and the results known internationally through publications and participation in international projects. Participation in the project “Skills Integration and New Technologies” - SKINT- has been of particular importance. Riksantikvaren participated as a sub-partner in the Intereg. IVB-project from 2008-2012. The main aim of the project was to achieve better-integrated sustainable management in area planning processes, particularly in urban areas. Riksantikvaren wanted to highlight the consequences that water management can have for the preservation of both visible and non-visible archaeological deposits. Bryggen was used as an example.<sup>91</sup> Several of the partners from SKINT are now working as consultants and advisors on the groundwater project. As a result of SKINT there is now increased focus on the significance of good water management and the preservation of cultural heritage, and in recent years new R&D and research projects have been implemented in Norway.<sup>92</sup>





# 04

## OPERATION GROUNDWATER RESCUE

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Figure 4.1

## SUBSIDENCE

During the 1990s the owners of buildings within the World Heritage site noticed signs of damage to their buildings, damage that was linked to subsidence. Measurements were taken that showed that in some areas the annual rate of subsidence was 5-7 millimetres. Initially, vibration from vehicular traffic along the front of Bryggen was suspected to be the culprit, but it very soon became clear that the principal cause was lower than anticipated groundwater levels in the most badly affected areas.



Figure 4.2:1

Figure 4.1 Bredsgården tenement: shoring up buildings damaged by subsidence.  
Photo: E. Jensen, Stiftelsen Bryggen.

Figure 4.2:1-2 Monitoring and surveying methods.  
Drawings: Multiconsult AS/  
O. M Hansen, Alkymi Design.

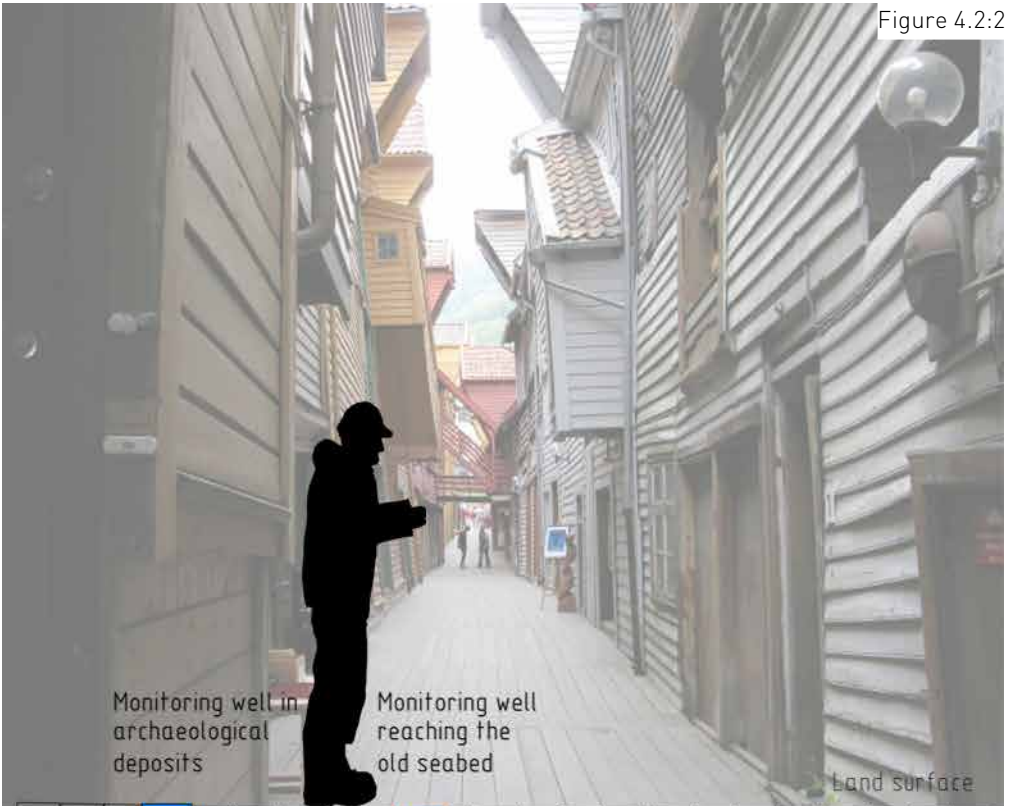


Figure 4.2:2

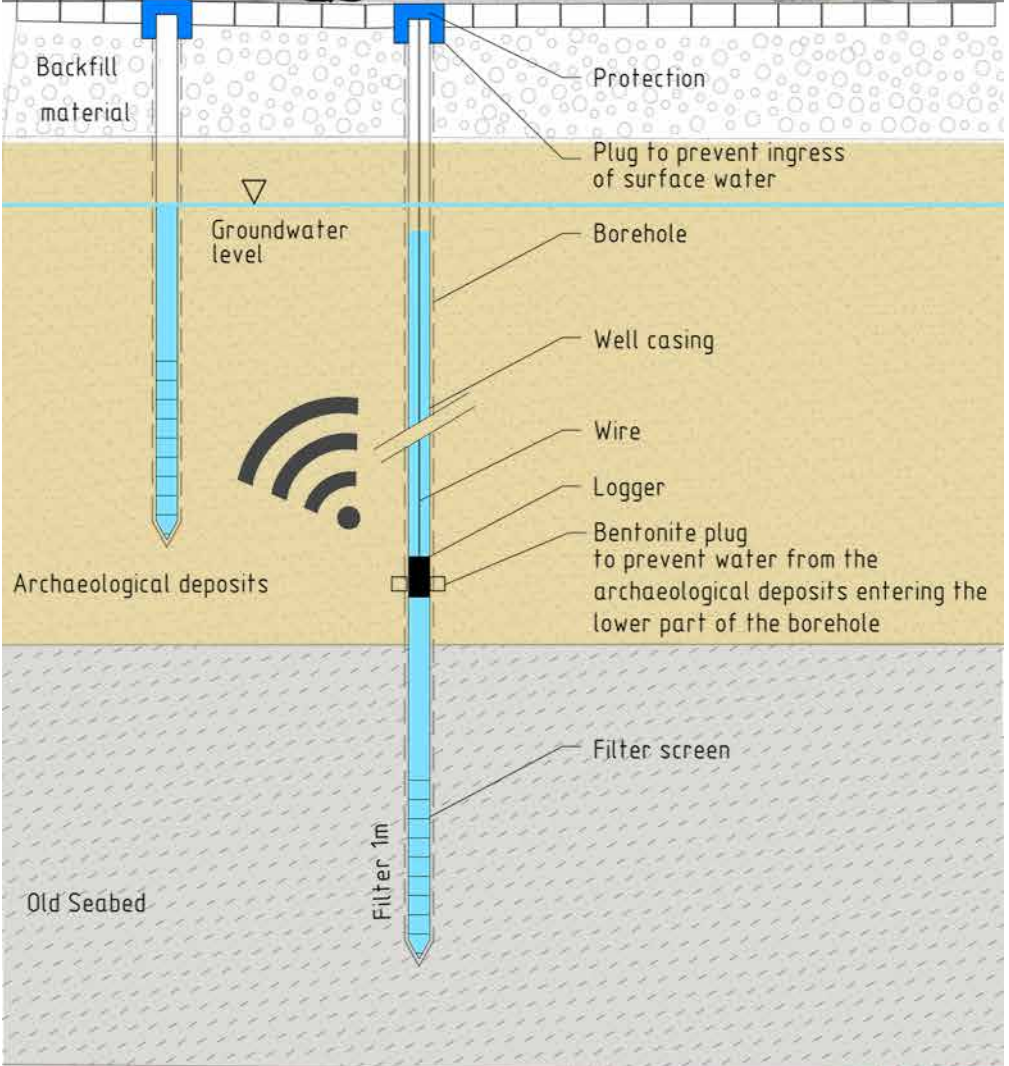






Figure 4.3

A comprehensive monitoring programme was designed to follow the groundwater situation, and by 2010 some 35 monitoring wells had been installed, along with a test-pit with various sensors placed at different depths in one of the soil walls.

Figure 4.3 Bryggen - sections showing buildings, archaeological deposits and groundwater.  
Drawing: T. Sponga, © Riksantikvaren.







Figure 4.4

After several years of monitoring the groundwater and subsidence, a pattern emerged that indicated that the reason for the lowered groundwater levels was the constant and considerable leakage of water into the site of the neighbouring hotel, which had been completed in 1982. To build the hotel, a wall of steel sheet piling had been rammed into the ground, enclosing the whole site. The wall’s primary purpose was to keep the earth walls around the construction site from collapsing, and to prevent flooding. Once the hotel was up, the contractor had little need for the sheet piling, and its removal was proposed. Fortunately, this never happened.

## OBJECTIVES AND SOLUTIONS

Based on the observations by the earliest investigations on subsidence and groundwater levels, carried out by Multiconsult in 2001, an interdisciplinary expert group was established to improve understanding of the situation and come up with a range of solutions. The expert group included archaeologists, hydrogeologists, chemists, conservation specialists, geotechnicians and representatives from Riksantikvaren and other stakeholders. Besides the geotechnical expertise at Multiconsult, key actors in the expert group were at

this stage the Norwegian Institute for Cultural Heritage Research (NIKU), the Geological Survey of Norway (NGU) and the National Museum of Denmark. From 2005 on, the expert group carried out important investigations including extended groundwater-level and subsidence monitoring, chemical analyses of water and soil, as well as archaeological observations. In 2009, an analysis of a range of different solutions to stop the dewatering was carried out by Multiconsult in close co-operation with the expert group, and based on their investigations.<sup>93</sup>

The solutions had to attain the following objectives:

- Raising of the water table in the most badly affected areas to levels as close as possible to those existing prior to the hotel’s construction (ideally, up to 1 m below the surface)
- Reducing groundwater flow to a minimum
- Reducing the diffusion of oxygen into the ground
- Reducing the rate of subsidence to 1 mm per year or less
- Reducing the average annual temperature in the deposits to 9 °C or less
- Ensuring a minimum of intervention in intact archaeological deposits
- To ensure that the weight loss of solids does not exceed 0.001% per year as a result of decomposition and leaching
- Securing, and if possible increasing, the supply of groundwater upstream

Figure 4.4 Column piling at the City Lade project, Trondheim, 2012. Photo: Jetgrunn AS.



Figure 4.5

Eight different measures were drafted and then weighed up against each other, based on assessments of a) their effectiveness in achieving the various objectives, b) construction costs, and c) operating costs. Taking all these factors into consideration, Multiconsult’s recommendation was to use a method of establishing a new wall of piles/jet columns and inject concrete/ bentonite into the bedrock beneath the sheet piling in towards the hotel.

In order to obtain an evaluation and quality assurance of Multiconsult’s proposals, the research institution SINTEF Building and Infrastructure was contacted. The proposals to use jet columns/piles and inject along and beneath the sheet piling were deemed to be sound and feasible, but there was some uncertainty concerning how solidly the piles could be anchored in the bedrock, whose surface was known to be severely fractured. Furthermore the method would require a concentration of heavy machinery in the construction area, which might inflict damage on both the standing buildings and the underlying archaeological deposits. It would, however, entail relatively small maintenance costs.

Figure 4.5 Raising the overflow level of the hotel’s drainage system. Photo: E. Rotevatn, Riksantikvaren.

SINTEF also became interested in, and requested additional clarification of, another of Multiconsult’s proposals, where the idea was to create an impermeable hydrological barrier from top to bottom on the outside of the sheet piling, and simultaneously raise the outflow level of the drainage system below the hotel as high as possible. This measure was expected to be cheaper in the construction phase, but would entail higher operational costs and follow-up.<sup>94</sup>

## FUNDING

Riksantikvaren decided, based on the Multiconsult and SINTEF evaluations along with all the other knowledge that had been developed in conjunction with the groundwater situation at Bryggen, that creating a hydrological barrier and raising the outflow level of the drainage system were the best mitigation measures. Riksantikvaren then began applying for funding for the concrete measures. Riksantikvaren informed the Ministry of Climate and Environment about the groundwater situation at Bryggen, and agreement was quickly reached that this was a matter that could be submitted for consideration in the Revised National Budget (RNB) in 2011. June 17th 2011 was a momentous day for the work with the ground conditions at Bryggen, when Parliament approved an RNB that included NOK 45 million earmarked for measures to stop groundwater leaking from the world heritage site.





Figure 4.6

Prior to this, at the end of 2010, Riksantikvaren had already contacted Statsbygg, the Norwegian government's key advisor in construction and property affairs, and asked them to take on the role of operative contractor for the groundwater project at Bryggen. At this time Riksantikvaren had fairly limited resources, and with this in mind the idea was firstly to plan the project in great detail, and secondly to carry out a limited amount of mitigation work. The size of Parliament's grant meant that this work could be considerably increased in relation to what had been planned, and a project group of experts who had already taken part in previous monitoring and planning work was supplemented with several new members.

The mandate from the Ministry of Climate and Environment stated that groundwater levels should be raised, the rate of decomposition of organic material should be slowed, and the rate of subsidence be reduced - but without the removal of more than a bare minimum of the rich archaeological deposits that we wished to preserve. This placed some restrictions on the types

of mitigation measures that could be implemented in certain areas. In order to assess whether the project's goals had been reached, quantitative targets were drawn up: broadly put, raising of the groundwater level to one meter below the modern surface, and a reduction of the overall annual rate of subsidence to one millimetre or less. Ambitious targets, but both necessary and not unrealistic. One of the key factors in the assessment of possible mitigation measures was the extent to which these were sustainable solutions. The project group therefore decided to explore Multiconsult's proposal concerning water infiltration along the outside of the sheet piling wall in more detail, while at the same time looking at other, smaller measures that could positively affect the groundwater level. It was also decided - and this was a significant strategic element - to carry out the various pieces of mitigation work in consecutive stages, so that the effects both major and minor measures could be documented and assessed as the project proceeded. This would enable any measure that displayed a negative effect to be stopped and reversed.

## MEASURES

In order to exclude as many sources of error as possible, the surface water and sewage pipes running below and in the immediate vicinity of the hotel were checked and repaired. In connection with this work, large holes where pipes ran through the sheet piling were discovered. It turned out that the level of the drainage outflow from the hotel was much lower than it had been when the hotel was new. Structural stability calculations showed that the groundwater level below the hotel could be raised by about 70 cm, and this was one of the first things to be done. The groundwater gradient between the hotel area and the world heritage site was thus significantly reduced, which immediately produced a documented positive effect on the groundwater level in the latter.

Parallel with these preliminary measures, a number of new monitoring wells were installed, and many of the area's complement of wells were equipped with automated loggers. Their data was transmitted, virtually in real time, to an online server so that the effects of the individual measures could be followed from day to day and assessed in relation to factors such as precipitation events and tidal variation. In order to map drainage pathways and leakages through the sheet piling, tracer tests were carried out. A clear pathway along outside of the sheet piling was detected, but the tests did not reveal any leaks in the wall itself; these were found during subsequent construction

Figure 4.6 Sealing of hole for one of the sheet piling's anchor stays. Photo: A. R. Dunlop, NIKU.



Figure 4.7

work. Still, the tracer tests made a respectable contribution to the process of selecting solutions.

One of the first tasks was to establish an infiltration system along the hotel's southeastern side. The system was to run along the outside of the sheet piling, where there was a chance that excavation work would encounter intact archaeological deposits. It was therefore important to trace the exact line of the sheet piling, which was done by means of a kind of metal detector when an electrical current was sent along the steel wall. In addition, a number of exploratory drillings were carried out in order to determine how far down it was to intact deposits.<sup>95</sup>

The terrain in the area where the first infiltration trench was to be located is a small incline, and for that reason a number of thresholds or dams were constructed to achieve an acceptable groundwater level in relation to the adjacent historic buildings; seen in longitudinal section, the trench comprises a series of steps - something like the locks in a ship canal. (The system is described in greater detail elsewhere in this book.) The drainpipes from all the neighbouring buildings - both modern and historic - were connected to the system, and municipal drinking water was

Figure 4.7 Construction of permeable pavement behind Bredsgården. Photo: A. R. Dunlop, NIKU.

initially used as a supplementary source of water. It was found that a lot of water was disappearing from some of the trench sections, so excavations were carried out along the inside of the sheet piling wall. Holes were discovered where the wall had been cut to accommodate the anchor stays; in addition, there were fractures between some of the piles, and there were areas where the top of the sheet



Figure 4.8

Figure 4.8 Rainwater garden under construction. Photo: A. R. Dunlop, NIKU.





Figure 4.9

piling had been cut down to a level that was lower than what the project required.

Sealing the sheet piling proved to be exacting work, because it was often hard to find all the leakage points before the trench had been backfilled and water had begun flowing along it. When a previously undetected leak was discovered, part of the trench had to be re-excavated. Drinking water was used to find the leakage points and it also made it possible to measure the size of the leak.

Because the hotel was undergoing renovation work, it was not possible to start the work on the infiltration trenches on the northeastern side of the hotel and around Schøtstuene (this is a suite of historic buildings set in grounds just to the northeast of the hotel) in 2012. Mitigation work during this period therefore centred

on channelling surface-/rainwater. Downpipes were sunk into the ground rather than being so connected to the drainage systems that remove water from the area, and the cobblestone surface in parts of Bryggen was converted into permeable pavement, whereby the fine-grained fill between the stones was replaced with coarser fill to facilitate infiltration. And a couple of the grassy areas behind the Bredsgården tenement that had previously had a convex or flat surface were reshaped as shallow depressions, known as swales, where rainwater could collect and percolate slowly into the ground.

### SUSTAINABLE INFILTRATION SYSTEM

Measurements of groundwater levels and subsidence rates showed that the system had begun to work in those areas where it had been installed. Given the aim of making the system as sustainable as possible, the intention has all along been to reduce the use of drinking water to a minimum. While waiting for access to the

Figure 4.9 Bryggen’s catchment area; arrows mark the various water flowpaths. Drawing: Multiconsult AS.

remaining areas, we discussed ways of getting water into the ground during periods with little or no precipitation. The first plans involved building some relatively large storage tanks to be placed beside the revetting wall along the street above Bryggen (Øvregaten, the medieval High Street), where water could be collected in rainy weather. Because of the archaeological deposits, it would not be possible to bury the tanks; instead they would have to be placed on the surface and concealed behind a stone wall built similarly to the revetting wall. Another suggestion concerning storage was to build a rainwater garden in the area just above the swales, where rainwater could be collected and infiltrated slowly.

However, questions were raised about the overall benefits of such tanks. For one thing, the control systems for automated filling and emptying would be relatively complicated - which conflicted with the project’s guiding principle to strive for simplicity with regard to maintenance in future operating phases. In due course, the plans for the storage tanks were set aside following discussions with representatives from Bergen municipality, who came up with a proposal to use surface water from the catchment area on the upper side of Øvregaten to fill the rainwater garden; one additional point was that the soil in the garden would filter out pollutants from the water prior to infiltration.

The hotel’s renovation was completed in the spring of 2013 and work could begin on installing the infiltration systems in the northeastern part of the area. The design of the system along the sheet piling was similar to the one that had been built the previous year, apart from the steps as the terrain here was almost horizontal. The Schøtstuene building suite is at a higher elevation than the adjacent hotel and is partly built on relatively recent soil. It was necessary to create a separate I/T-system for this area, with a connection down to the main I/T-system. Two small water-storage tanks were buried on the northeastern side of the buildings; these will help supply water to the pipes that encircle the buildings. Only the pipes along the buildings’ southwestern side are made for infiltration. The reason for this is that there is a medieval stone ruin under the building suite’s eastern corner. The ruin stands on timber foundations and organic deposits that need to be kept wet - whereas the walls need to be kept dry. This means that we cannot infiltrate water too close to the ruin, and groundwater level in this area cannot exceed ca. 4 metres asl. Monitoring the situation over a longer period of time will show whether or not the infiltration is working as intended.

Despite all the work to seal the sheet piling, water is still leaking out of the world heritage site faster than desired. The reason for this may be holes in the sheet piling below the level to which it was possible to excavate, or below the base of the sheet piling, or in fractures in the bedrock. In order not to have to continue using drinking water to replenish the system, other stable water sources were considered. Measurements showed that there was still some excess water under the hotel despite the fact that the drainage outflow level had been raised considerably. Two water pumps were sunk into the ground on the inside of the sheet piling in the area between the hotel and Schøtstuene. Their intakes are at a level slightly below the highest permitted water level around the hotel (if the water level gets too high, there is a risk that the hotel might break free from its foundations and pop up like a cork), so there is a ‘reservoir’ of water in the hotel area that the project can tap into. This excess water is pumped back into the I/T-system on the other side of the sheet piling, thus also forming a kind of water barrier that helps to keep the groundwater level in the Schøtstuene area stable. A control room has been outfitted in the cellar beneath Schøtstuene; from this room the water supply to individual sections of the I/T-system can be regulated with a high degree of flexibility, and it is where the pumps are connected to the electrical mains.

### MAINTENANCE AND MONITORING

The final major piece of construction work to be completed is to channel surface water from the catchment area above Bryggen and direct it to the rainwater garden, the storage tanks and the ground in general; this will be done in collaboration with Bergen municipality’s water and sanitation department.

Even though the system has now been more or less completed, it will take a long time to saturate the ground to the extent where the groundwater situation becomes stabilized at the desired level. A plan has been drawn up for continued intensive monitoring over the next five years with on-going evaluation of the systems. After that it will be possible to see if the goals have been achieved - and if that turns out to be the case, then the intensity of monitoring can be reduced accordingly.



# 05

## ARCHAEOLOGICAL ASPECTS

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Archaeological assessment of state of preservation forms one of the mainstays in the overall work of environmental monitoring with regard to the organic deposits found in Norway’s medieval towns. Specialists such as Henning Matthiesen of Denmark’s National Museum’s Conservation Department and Ove Bergersen of Bioforsk Jord og miljø have stated on numerous occasions that the archaeological assessments of the state of preservation of organic contexts represent essential information in connection with their own analysis and interpretation of preservation conditions below the ground surface. And heritage managers naturally rely heavily on the archaeological assessments, since it is difficult to manage such a complex phenomenon as a medieval town without knowing the current condition of its buried components. This chapter will therefore present the archaeological side of monitoring work, with particular emphasis on the Bryggen WHS.

## ASSESSMENT OF STATE OF PRESERVATION OF ORGANIC CONTEXTS

The growing focus on monitoring of organic archaeological deposits in Norway has necessitated regular revision of recording methods so as to incorporate more information about the state of preservation of investigated deposits and their contents. Such revisions have been undertaken during the past 20 years by NIKU (the Norwegian Institute for Cultural Heritage Research), which was established in 1994 and is responsible for carrying out all archaeological investigations in Norway’s medieval towns and at other kinds of medieval sites outside the towns. Nowadays, assessment of the state of preservation of organic remains is standard practice on all such investigations, whether large-scale excavations, small test-pits, watching briefs (i.e. archaeological supervision and recording in connection with ditch digging), or drillings for the installation of monitoring wells, and has been incorporated in the Norwegian Standard NS9451.<sup>96</sup>

### Assessment methods

Assessment of the state of preservation of the various organic components found in any given context is based on the following principal criteria/indicators:

- Odour:
  - for organic contexts: presence and strength of ‘rotten-egg’ smell
  - for wood: presence and strength of “freshly cut” smell
- Colour/colour change: the brighter the soil’s colour when first exposed and the faster the rate of colour change (darkening) after exposure, the better the preservation
  - rate of darkening comprises four categories:
- none
- fast - mere seconds
- medium - up to ca. one minute
- slow - more than ca. one minute
- Tension/fracture:
  - for woodchips/pieces of wood: the amount of force required to snap pieces of wood - the more force, the better the preservation (for this purpose, relatively thin woodchips or twigs should be chosen, not naturally hard pieces such as knots)
  - for moss: the amount of force required to pull apart a strand of moss
- Strength/structure:
  - the amount of ‘sponge reaction’ (elasticity) exhibited when pressure is removed after a block of the context has been lightly compressed between thumb and index finger
  - the amount of force necessary to squeeze a woodchip/ piece of wood between thumb and index finger
- Suppleness:
  - suppleness of pieces of leather
  - springiness of strands of moss or hair/fur
- General appearance (colour, visibility of structure) of macroscopic organic components

The image shows a screenshot of the FELTDOKUMENTASJONSDATABASE (FDB) 1.0 form. The form is divided into several sections: PHYSICAL PROPERTIES, BOTANICAL COMPONENTS, ZOOLOGICAL COMPONENTS, MINERAL COMPONENTS, ARTEFACTS, and CONTEXT'S PROPERTIES. A red circle highlights the 'STATE OF PRESERVATION' section, which includes a dropdown menu for 'from scale' set to 'C4'. The form also includes fields for 'Reading no.', 'Value', 'Where taken', 'Soil type setting', 'Rate of accumulation', 'Mechanical factors', and 'Character'.

Figure 5.1

### The context recording form

All the relevant information for each individual investigated context is entered into a context recording form. The present context recording form, as refined by NIKU and incorporated into the field documentation database used by NIKU’s excavation offices, consists of five sheets. The sheet concerned with information related to state of preservation/monitoring is presented in Fig. 5.1 above (it would be impossible to go through and describe the form in detail here and now; the important thing in connection with this discussion is to highlight those aspects directly connected with the archaeological assessment of state of preservation).

The context recording form constitutes the backbone of the archaeological recording system. The guiding premise behind it is that a layer’s physical properties/attributes, cultural contents and stratigraphic relationship to other layers and/or structures - in short, an assessment of the whole context - will reflect the nature, conditions and approximate duration of its formation, together with any subsequent transformations.

The form seeks to eliminate the element of subjectivity as far as possible, but it nevertheless has to be admitted that, in the final analysis, assessment of a context’s overall state of preservation depends to a great extent on the individual archaeologist’s accumulated experience of working with organic deposits.

### State of Preservation Scale

The recording form culminates with its possibly most important field, particularly with a view to monitoring and mapping work: STATE OF PRESERVATION (see red ellipse in Fig. 5.1 above).

This is where the alphanumeric value of the individual context’s overall state of preservation is entered. The correct value can be determined by reference to Fig. 5.2 next page - the State of Preservation Scale - always provided one has established the (average) elevation of the watertable.

The scale runs from 0 to 5, and is meant to be absolute - and independent of position in relation to groundwater level (i.e., a context designated A5 will contain material just as well preserved as material in a context designated C5). A score of 0 means that the context is completely inorganic, at least from the archaeologist’s point of view. The highest score, 5, corresponds to the best state of preservation observed at Bryggen - ideally, the best-

Figure 5.1 Sheet for state of preservation/monitoring information in the context recording form. Illustration: A. R. Dunlop, NIKU.

STATE OF PRESERVATION

		DEGREE OF PRESERVATION					
		None	Lousy	Poor	Medium	Good	Excelent
Proposition relation to groundwater	- Over	A0	A1	A2	A3	A4	A5
	- Over/In	B0	B1	B2	B3	B4	B5
	- In	C0	C1	C2	C3	C4	C5
		0	1	2	3	4	5
Figure 5.2	Fill etc. later than ca. 1900	D0	D1	D2	D3	D4	D5

preserved organic material should look and feel like it had been deposited only yesterday - and Bryggen is believed to be the site where organic material exhibiting the best state of preservation so far encountered is to be found (but see discussion a little further down the page).

The lay-out of the form also makes it possible to enter the state of preservation of every kind of organic component found in the context (in recognition of the fact that differential preservation does indeed occur). The green ellipse in Fig. 5.1 marks the listed botanical components, whose state of preservation is shown in the column headed 'Pres.'.

The State of Preservation Scale gives the impression of being an absolute scale (and possibly it should be, in theory). However, it has been noticed that it is hard for the recording archaeologist to make assessments in relation to an absolute scale of state of preservation. Obviously, it is not possible for all archaeologists to have precisely the same notion of what represents optimal state of preservation. Moreover, perhaps the question is whether there can even be such a thing as an optimal state of preservation in absolute terms. We may point to a certain deposit now and characterize its state of preservation as excellent, but if all organic deposits are undergoing decomposition, however gradual - there being

no such thing as a stable burial environment, as has been repeatedly pointed out - then how much better must not its state of preservation have been 100 years ago? And anyway, what situation are we to hold up as a yardstick? How could we ever be sure that we have encountered deposits exhibiting optimal state of preservation - even at such a site as Bryggen?

However, having said all that, the scale can at least be applied universally and thus facilitates comparison between, for instance, archaeological state-of-preservation assessments and geochemical findings regarding preservation conditions.

PRACTICAL APPLICATIONS

There are numerous ways to use the information in the context recording form, and these are presented in the following sections.

Comparison of contexts

One of the context recording form's great advantages is the facility of assigning a numeric value to the different variables within each of the categories of physical properties and components as exemplified by the red ellipses in Fig.5.3 opposite page.

The same thing can be done with the variables in the different property categories under the four component types - botanical, zoological, mineral, and artefactual - that make up any given deposit (see Fig. 5.4 opposite page).

Figure 5.2 The State of Preservation Scale.  
Modified from Norsk Standard 2009, NS9451:2009.

PHYSICAL PROPERTIES/ATTRIBUTES

COLOUR		basic		additional		shade				
COLOUR CHANGE		darkening/no darkening				(other)				
RATE OF CHANGE		none = 1		fast (seconds) = 2		medium (up to 1 min.) = 3		slow (minutes) = 4		
ODOUR TYPE		none/earthy = 1	pollution (oil/ diesel) = 2		H <sub>2</sub> S = 3		salt = 4	dung/excrement = 5		freshly cut wood = 6
ODOUR STRENGTH		absent = 1		faint = 2			medium = 3	strong = 4		overpowering = 5
SURFACE		regular = 1		undulating = 2			indented (sharp) = 3	uneven = 4		uneven (sharp) = 5
LIMES		sharp transition = 1		interference < 2 mm = 2		interference < 5 mm = 3		interference < 10 mm = 4		interference > 10 mm = 5
HOMOGENEITY		1 component, uniform structure = 1		1 component, variable structure = 2			several components, uniform structure = 3	several components, variable structure = 4		differentiated groups = 5
LAMINATION		absence = 1		horizontal components = 2		groups in lenses = 3		stratified lenses = 4		multi-layer = 5
COMPACTNESS		loose structure = 1		easily separated = 2			loose block = 3	block = 4		hard block = 5
ELASTICITY		plastic/loose = 1		slight reaction = 2			visible reaction = 3	almost sponge = 4		sponge reaction = 5

Figure 5.3

BOTANICAL COMPONENTS					
PRESERVATION	decomposed = 1	← 25% = 2	← 50% = 3	→ 50% = 4	→ 75% = 5
INCLINATION	indefinable = 1	→ 75% parallel = 2	→ 50% parallel = 3	angled = 4	random = 5
DISTRIBUTION	indefinable = 1	uniform = 2	non-uniform = 3	irregular concentrations = 4	regular concentrations = 5
MECH. FACTORS	indefinable = 1	absence = 2	fungus/insect attack = 3	cut = 4	burnt = 5

ZOOLOGICAL COMPONENTS					
PRESERVATION	crumbled = 1	fragments = 2	pieces = 3	large pieces = 4	full size = 5
INCLINATION	indefinable = 1	→ 75% parallel = 2	→ 50% parallel = 3	angled = 4	random = 5
DISTRIBUTION	indefinable = 1	uniform = 2	non-uniform = 3	irregular concentrations = 4	regular concentrations = 5
MECH. FACTORS	indefinable = 1	weathered = 2	cut/split = 3	crushed = 4	burnt = 5

MINERAL COMPONENTS					
INCLINATION	indefinable = 1	→ 75% parallel = 2	→ 50% parallel = 3	angled = 4	random = 5
DISTRIBUTION	indefinable = 1	uniform = 2	non-uniform = 3	irregular concentrations = 4	regular concentrations = 5
MECH. FACTORS	indefinable = 1	leached = 2	eroded/abraded = 3	crushed = 4	burnt = 5

ARTEFACTS					
INCLINATION	indefinable = 1	→ 75% parallel = 2	→ 50% parallel = 3	angled = 4	random = 5
DISTRIBUTION	singly = 1	random = 2	irregular concentrations = 3	regular concentrations = 4	regular concentrations in horizons = 5
MECH. FACTORS	indefinable = 1	residual/intrusive = 2	abraded = 3	crushed = 4	burnt = 5

Figure 5.4

Figure. 5.3 Numerical values assigned to variables within categories of physical properties.  
Illustration: A. R. Dunlop, NIKU.

Figure 5.4. Numerical values assigned to variables within the categories under the four component types.  
Illustration: A. R. Dunlop, NIKU.



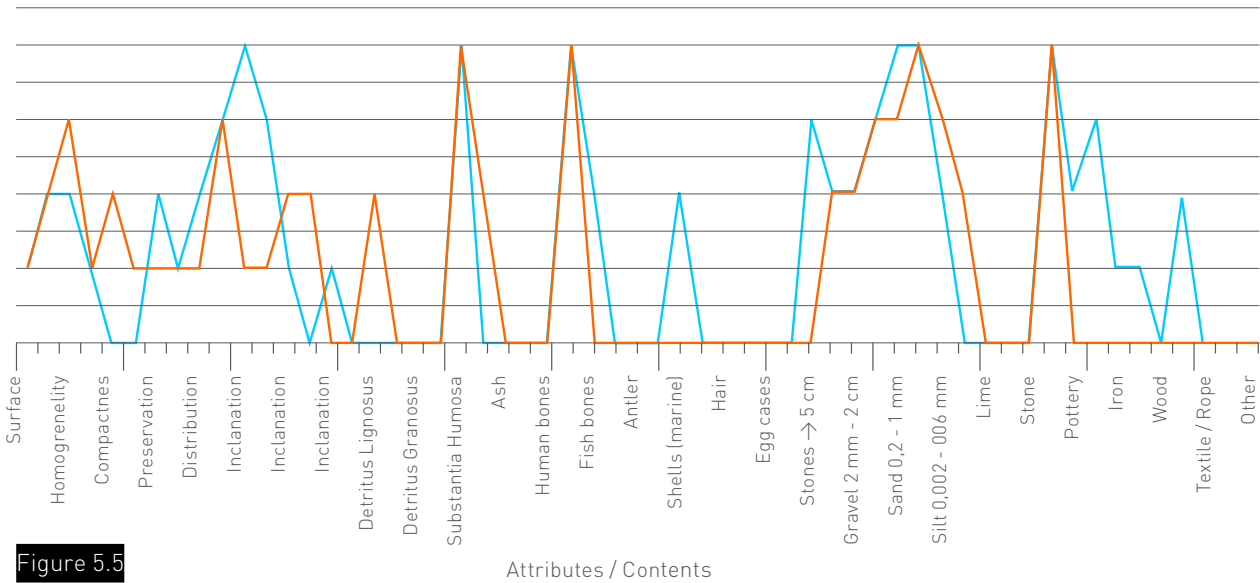


Figure 5.5

These values can then be plotted in Microsoft Excel and presented in the form of a graph - which provides, in effect, a ‘signature’ of the layer (see example diagram Fig. 5.5 above page). This enables comparison of two or more contexts found on an excavation site: to determine, for instance, whether or not they really form part of the same deposit.

Detection of temporal variation

Archaeological assessments of state of preservation represent baseline data. In the context of deposit monitoring, this allows comparison of a context that has been recorded on two or more separate occasions. And this in turn enables the archaeologist to detect whether or not there has been any change - ‘change’ will almost always imply deterioration - in the investigated context’s state of preservation.

Opportunities for detecting temporal changes can arise in several ways:

Figure 5.5 Comparison of layer ‘signatures’. Illustration: A. R. Dunlop, NIKU.

- when an excavation is carried out immediately adjacent to a previous excavation site
- when a test-pit is re-excavated
  - at Bryggen, the test-pit known as ‘Henning’s hole’ was originally excavated in 2006<sup>97</sup> and re-excavated in 2010
- no deterioration was recorded, but it must be noted that the organic deposits in this test-pit were already very decomposed, so it would be very difficult to detect deterioration in the course of an interval of no more than five years
- when a ditch is re-excavated
- when a new drilling is carried out close to an existing monitoring well
  - at Bryggen, this has so far occurred three times:
- in 2009, monitoring well MB15<sup>98</sup> was installed close to monitoring well MB13<sup>99</sup>, which had been drilled in 2005; this case will be presented in section 4.2 (deterioration was detected)
- in 2012, the bedrock monitoring well designated FJB3<sup>100</sup> was installed close to monitoring well MB23<sup>101</sup>, which had been drilled in 2006; this case will be discussed in section 3.4, but to illustrate a different aspect (no deterioration was detected)
- in 2013, a drilling designated UW01<sup>102</sup> - undertaken in connection with the project Urban WATCH - was carried out close to monitoring well MB21<sup>103</sup>, which had been drilled in 2006 (no deterioration was detected)

MB39	Masl	SYMBOLS
§§§§§	3.0 – 2.0	X - LOUSY
XXXXX	2.0 – 1.0	X - POOR
XXXXX	1.0 – 0.0	X - MEDIUM
XXXXX	0.0 – -1.0	X - GOOD
XXXXX	-1.0 – -2.0	X - EXCELLENT
XXXXX	-2.0 – -3.0	§ - INORGANIC
00000	-3.0 – -4.0	? - INDEFINABLE
NNNNN	-4.0 – -5.0	0 - NO SOIL RECOVERED
NNNNN	-5.0 – -6.0	N - NATURAL
NNNF	-6.0 – -7.0	F - BEDROCK

Figure 5.6

Identification of redeposited material

Referring to Fig. 5.6 above (which presents the state of preservation of the deposits in monitoring well MB39<sup>104</sup>), one should take note of the two red ellipses. These surround two contexts that exhibit a poor state of preservation (red Xs), but that are sandwiched between deposits exhibiting either good (green Xs) or excellent (purple Xs) preservation.

Such disparity - especially at such depths - must mean that the two poorly preserved contexts consist of material that had become well decomposed before it entered the archaeological record. This case shows that assessments of state of preservation can make significant contributions to interpretations of an area’s depositional history.

Figure 5.6 Schematic presentation of state of preservation (archaeological assessment) of the deposits in monitoring well MB39. Each individual symbol represents a length of about 20 centimetres, and depth from the surface increases from left to right within each cell. Illustration: A. R. Dunlop, NIKU.

FJB3 (2013) (Dunlop/Lorvik)	MB23 (2006) (Dunlop)	Masl
00000	?????	2.0 – 1.0
XXXXX	?XXXX	1.0 – 0.0
XXXXX	XXXXX	0.0 – -1.0
00000	XXXX0	-1.0 – -2.0
XXXXX	XXXXX	-2.0 – -3.0
XXXXX	XXXXX	-3.0 – -4.0
XXXXX	XXXXX	-4.0 – -5.0
XN	XXXN	-5.0 – -6.0

Figure 5.7

Control of variation between individual archaeologists

Even the degree of agreement in assessments undertaken by different archaeologists can be checked. Such an opportunity occurred in 2013, when the bedrock monitoring well FJB3 was drilled close to monitoring well MB23, which had been installed in 2006 (see Fig. 5.7 above). The archaeological recording of MB23 in 2006 was carried out by Dunlop, who also recorded the upper four metres of FJB3 (i.e., down to c. -2.0 metres above sea-level) in 2013. The bottom four metres of FJB3 (highlighted by the red rectangle) were recorded by Dunlop’s colleague at NIKU’s Bergen office, Katharina Lorvik, and one can easily perceive that the degree of correspondence is eminently acceptable (and any discrepancies between the two sequences can be explained).

Figure 5.7 Schematic comparative presentation of state of preservation (archaeological assessments by Dunlop and partly by Lorvik) of the deposits in dipwell MB23 and bedrock monitoring well FJB3. Each individual symbol represents a length of about 20 centimetres, and depth from the surface increases from left to right within each cell.<sup>105</sup> Illustration: A. R. Dunlop, NIKU.

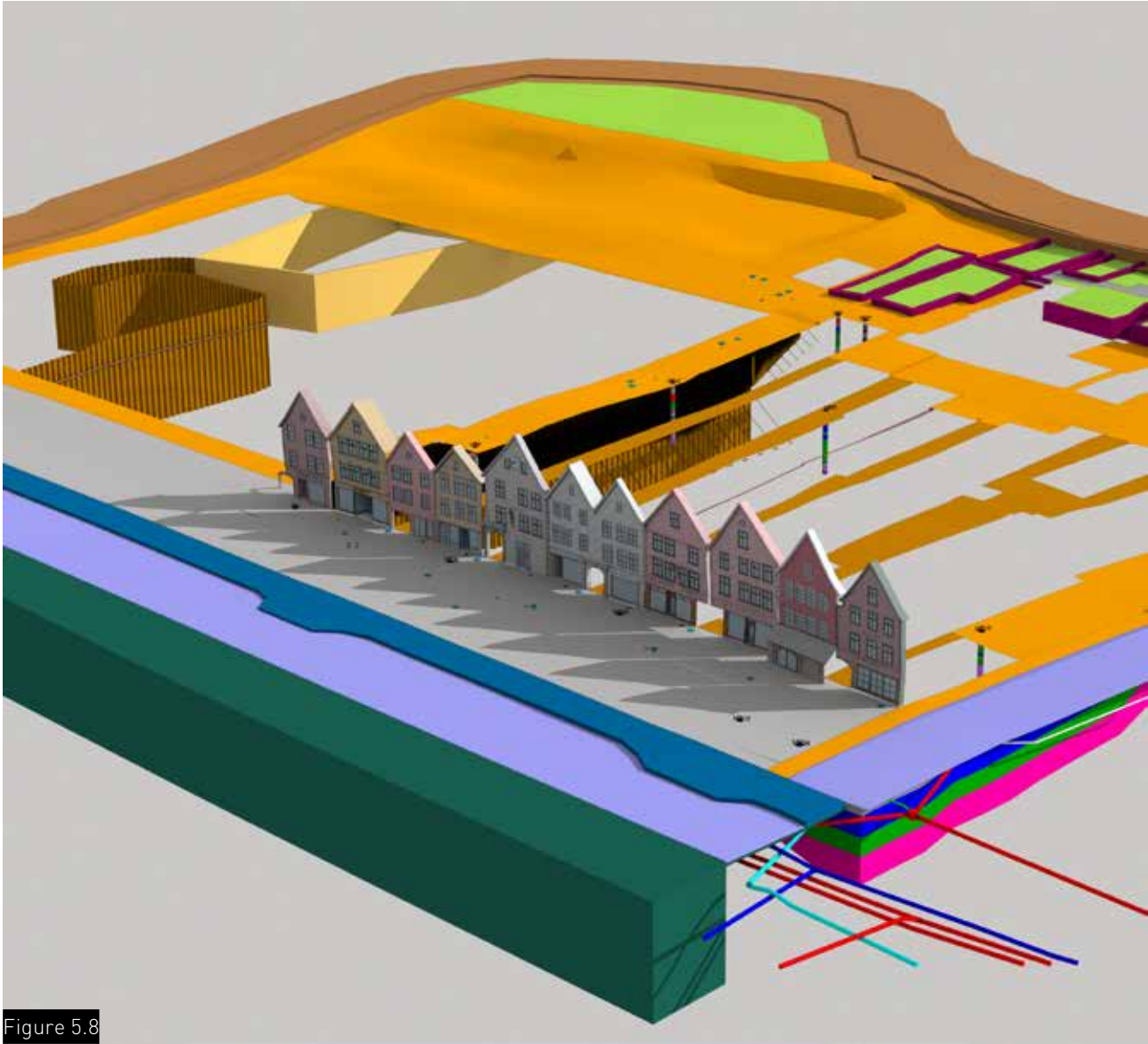


Figure 5.8

## REVIEW OF STATE OF PRESERVATION SITUATION AT BRYGGEN

It will not be possible to go into detail here, but there are a number of 2D and 3D models, produced by Gładki and by de Beer, that show the situation admirably, as exemplified by Fig. 5.8.

### Overall situation

Matthiesen has drawn up a map (Fig. 5.9) where Bryggen is divided into four zones based on a) mechanisms governing preservation conditions<sup>106</sup>, and b) to some extent observed preservation conditions. Based on the available information - mostly from the 40+ drillings carried out within the Bryggen area - there appears to be quite good correspondence with the overall state-of-preservation picture.

Figure 5.8 Model of state of preservation of archaeological deposits under Bryggen.  
Drawing: M. Gładki, PAST S.C.

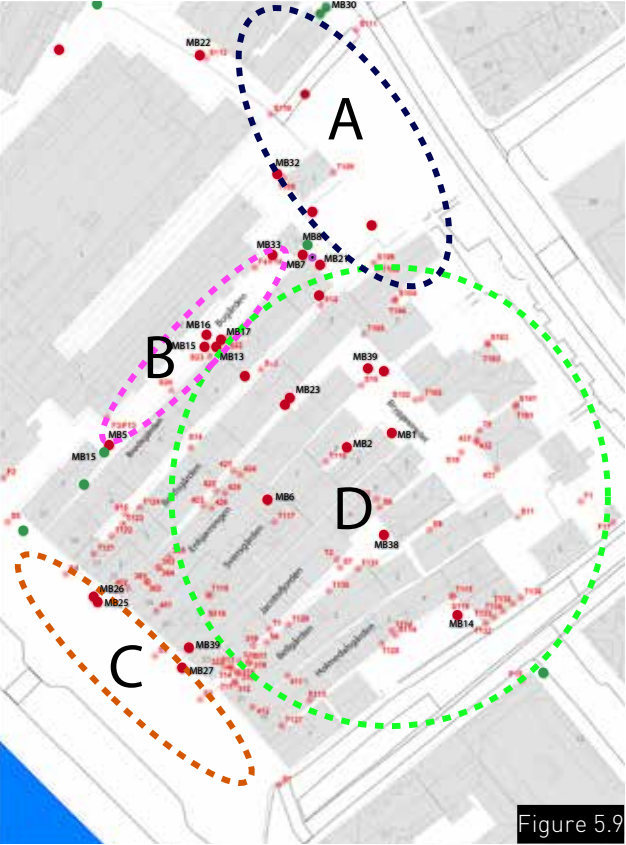


Figure 5.9

The factors relating to the state-of-preservation situation in each of the four zones will be described briefly in the following.

Zone A is characterized by:

- relatively thin archaeological deposits in general
- relatively high degree of modern disturbance (Koren Wiberg's Schøtstuene<sup>107</sup> and Peterskirken<sup>108</sup> excavations, and the leaking wall of sheet piling enclosing the hotel site)
- most severely affected/threatened by dewatering hopefully now remedied by various mitigation measures designed to raise the water-table in this zone
- broadly speaking, an unsatisfactory state of preservation (which cannot be reversed, no matter how much one manages to raise the water-table), but there are exceptions, such as monitoring well MB7, where deposits displaying an excellent state of preservation are encountered at a little more than five metres below the ground surface<sup>109</sup>

Figure. 5.9 Matthiesen's map showing Bryggen divided into four zones characterized by differing preservation conditions.  
Modified from Matthiesen et al. 2008.

Zone B is characterized by:

- thick archaeological deposits
- high degree of modern disturbance (the leaking wall of sheet piling enclosing the hotel site)
- affected/threatened by dewatering to a certain extent, and (in the upper deposits) by the flow of rainwater along the sheet piling - the effects of the latter mechanism have hopefully now been considerably reduced by means of a series of bentonite dams
- pronounced vertical disparity in state of preservation:
  - from the surface and down to about four metres below the surface the deposits generally exhibit a poor state of preservation
  - from about four metres below the surface the deposits generally exhibit a good state of preservation, with some even meriting an assessment of excellent (but see next section)

Zone C is characterized by:

- thick archaeological deposits
- low degree of modern disturbance (almost exclusively in the deposits immediately below the surface)
- high proportion of loose, sandy, relatively permeable deposits down to as much as 5 metres from the surface
- affected/threatened by ingress of salty water over several centuries
- same pronounced vertical disparity in state of preservation as in zone B - but no deposits yet found in zone C exhibit an excellent state of preservation

Zone D is characterized by:

- generally thick archaeological deposits
- low degree of modern disturbance (almost exclusively in the deposits immediately below the surface)
- stable and generally high water-table
- general absence of serious threats
- a very satisfactory state of preservation for the most part

Environmental monitoring of the deposits will naturally be the most important way of detecting any changes in preservation conditions, but in the author's view it would be valuable to supplement the monitoring work with an occasional drilling to check up on the state of preservation as well. Ideally, any such drillings should be carried out close to existing monitoring wells to allow detection of any deterioration in state of preservation (see next section).



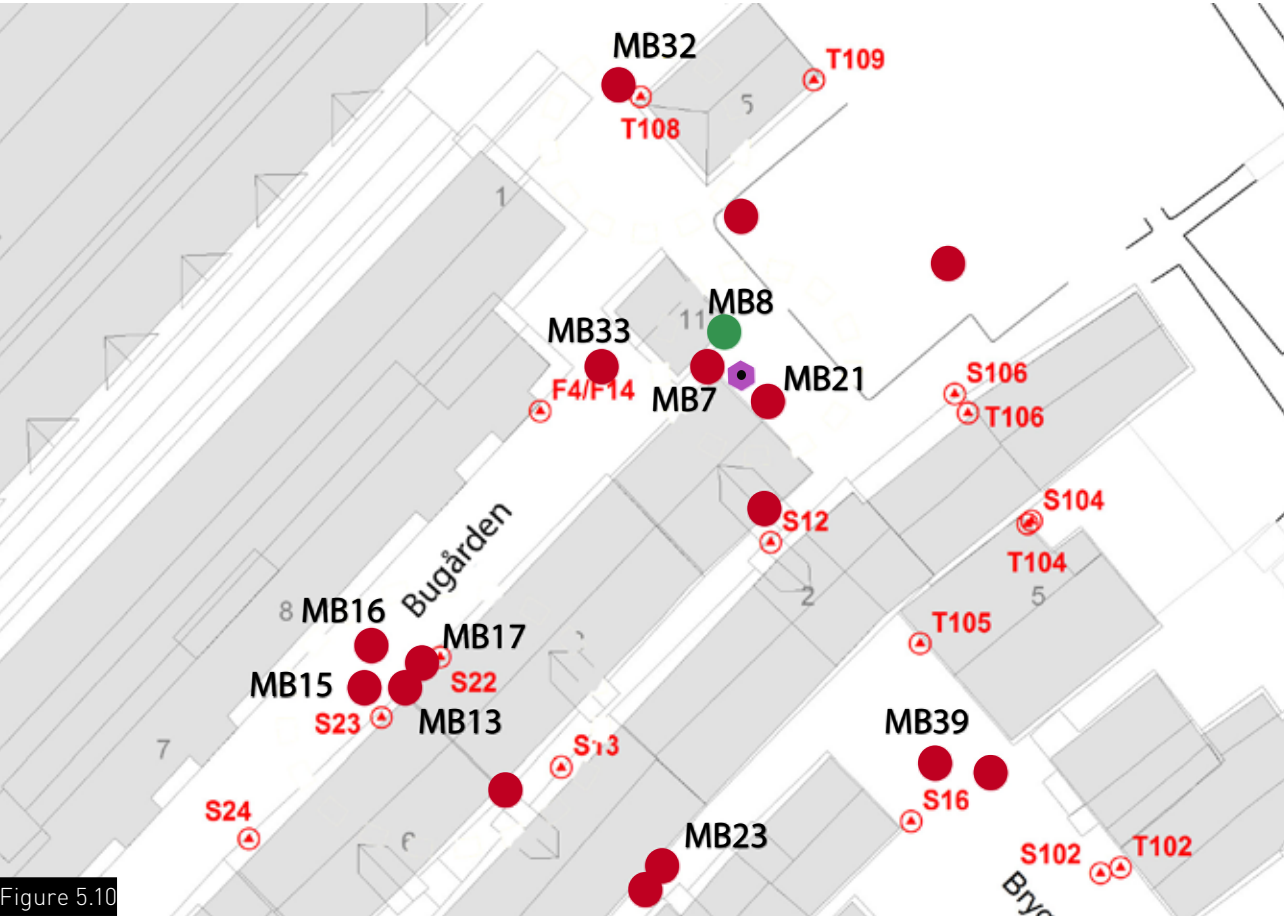


Figure 5.10

Documented case of deposit deterioration (MB13/MB15)

So far, there has been only one documented case - within the time frame of the Bryggen monitoring project at least - of deterioration in the state of preservation of an archaeological deposit lying at great depth. This occurred when monitoring well MB15 was installed close to monitoring well MB13 (Fig. 5.10) in what was formerly part of the eavesdrop between the northern Bredsgården tenement and the southern Bugården tenement, MB13 having been drilled in 2005, MB15 four years later.

The following remarks are from the original report<sup>110</sup>: In MB15 we have seen, for the very first time at Bryggen, concrete indications of a change for the worse in the state of preservation of organic deposits compared with a situation recorded only four years previously (in MB13). Furthermore, this worsening has occurred in strata at a very deep level, something that nobody would really have expected.

The first thing to ask is whether there are any potential sources of error. The answer to this is that there are no obvious ones. The two archaeological assessments involved were carried out by the same person (Dunlop) and under roughly similar conditions. The methods employed (including the drilling work itself) in 2009 were the same as in the previous investigation.

This development is extremely alarming. It would seem to indicate an ongoing - and serious - deterioration of deep-level preservation conditions. Confirming this deterioration and determining the possible causal factors is a task for geochemist Matthiesen and hydrogeologist de Beer, but to this archaeologist at least the fact that

Figure 5.10 The approximate positions of monitoring wells MB13 and MB15.  
Map: A. Seither, NGU.

MB15 (2009)	MB13 (2005)	Masl	SYMBOLS
		3.0 – 2.0	§ - INORGANIC
?????	?????	2.0 – 1.0	X - VERY POOR
?????	??XXX	1.0 – 0.0	X - POOR
?X???	XXXXX	0.0 – -1.0	X - MEDIUM
X??XX	XXXXX	-1.0 – -2.0	X - GOOD
§XXXX	XXXXX	-2.0 – -3.0	X - VERY GOOD
X§XXX§	XXXXX	-3.0 – -4.0	? - INDEFINABLE
XXXXX	XXXXX	-4.0 – -5.0	0 - NO SOIL RECOVERED
XXXXX	XXXXX	-5.0 – -6.0	N - NATURAL
XA(N)	N	-6.0 – -7.0	A - DRILLING ABANDONED

Figure 5.11

this is occurring right next to the sheet piling encircling the hotel site strongly suggests that more than coincidence is involved.

In Fig. 5.11 above, the deposit in question is marked by the red ellipses, going from c. -4.4 to c. -6.0 metres above sea-level. The deposit in MB13 was judged to have an excellent state of preservation in 2005, but when the corresponding deposit in MB15 was examined in 2009, its state of preservation had dropped to only good. This is - in terms of state of preservation - a kind of quantum jump in the wrong direction, according to Matthiesen (pers. comm.).

Figure 5.11 Schematic comparative presentation of the state of preservation (archaeological assessment) of the deposits in monitoring wells MB15 and MB13. Each individual symbol represents a length of about 20 centimetres, and depth from the surface increases from left to right in each cell.<sup>111</sup> Illustration: A.R.Dunlop, NIKU.

SCHØTSTUENE & ØVREGATEN (THE HIGH STREET)

Even though avoidance of conflict with intact archaeological remains was one of the Groundwater Project’s ruling principles, there were some instances where this was not possible, and this section presents perhaps the most important archaeological finding deriving from the project.

Modern-day Øvregaten passes very close to the eastern end of Mariakirken (St. Mary’s Church) - a very unusual configuration - and then bifurcates into two other roads: the thoroughfare of Øvre Dreggsallmenningen, which proceeds in a northwesterly direction, and Nye Sandviksveien, which proceeds in a northeasterly direction.

Physical remains of medieval Øvregaten have never been surely identified by archaeological investigations. It is therefore impossible to pinpoint the medieval street’s location and course purely on the basis of archaeological



information. However, some ‘circumstantial’ evidence has newly emerged that may provide an insight into Øvregaten’s high-medieval course in the neighbourhood of St. Mary’s Church.

In early 2014, excavation work in connection with construction of the water management system around the suite of historic buildings called Schøtstuene - which is part of the Bryggen WHS - brought to light a section of stone foundation (Fig. 5.12) running along the northeastern side of the suite’s northwesternmost building. (This was designated context 48 in the archaeological report<sup>112</sup>). Context 48 was aligned from northwest to southeast and could be followed for about eight metres. At its southeastern end there was a probable corner, where the foundation turned at right-angles to the southwest.

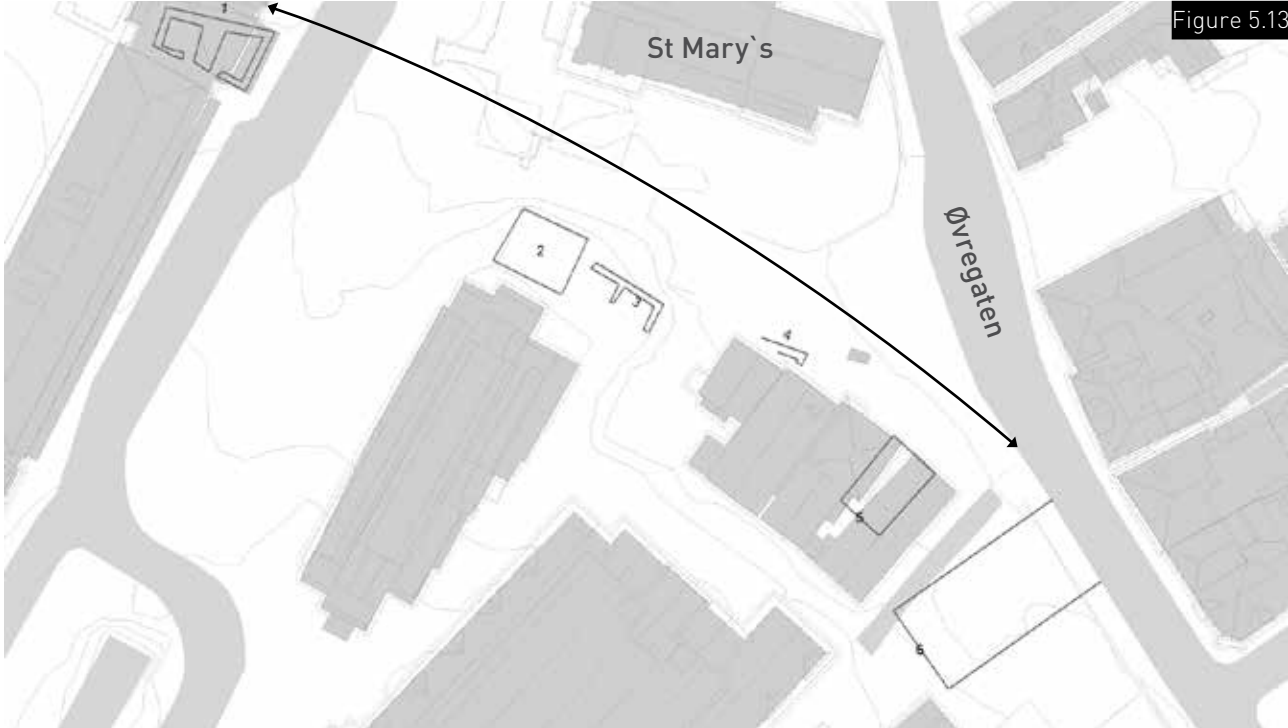
With this discovery, we now seemed to have an entire chain of stone buildings running north-west to south-east along the back of the Dreggen area and of Bryggen’s northern part; this is shown on Fig. 5.13 opposite page. Starting from the northwest, the chain comprises the following buildings:

- 1 - Katarinahospitalet (St. Catherine’s hospice): a refuge mostly for sick or destitute women and their children;
- 2 - Lavranskirken (St. Lawrence’s chapel): a small private church or chapel;
- 3 - Maria Gildeskåle: an ‘official’ building where the court of appeals met;
- 4 - context 48; no information about its function;
- 5 - an unnamed ruined stone building under the south-easternmost of the Schøtstuene buildings: no information about its function;
- 6 - Peterskirken (St. Peter’s Church)

The discovery of yet another building that slotted nicely into the row suggested that the observed configuration was not accidental. The most obvious hypothesis is that the chain of buildings indicates the course of a major thoroughfare: Øvregaten!

This hypothesis will have to be tested and discussed thoroughly, which will mean enlisting the help of an historian. Professor of History Geir Atle Ersland has already been approached - his response to the overture being positive - and the collaboration promises to be a stimulating one.

Figure 5.12 Context 48.  
Photo: A. R. Dunlop, NIKU.



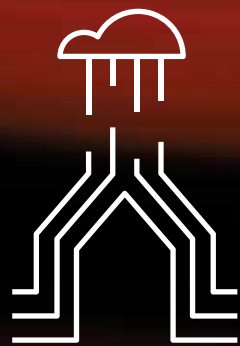
## CONCLUSION & FUTURE PERSPECTIVES

Of course, things never stand still for very long, and the planned introduction of all-embracing digital documentation systems for archaeological recording (such as Intrasis, which will shortly be employed by all of NIKU’s district offices) will undoubtedly bring changes with regard to archaeological state-of-preservation assessments - at least when it comes to lay-out and presentation forms, but the underlying principles will continue to apply in some form for the foreseeable future. The principal challenge is to put the assessment of state of preservation on a more rigorously scientific and more quantitative footing, and this is currently being looked into by two of NIKU’s archaeologists, who are participating in the project Urban WATCH. One possible method could involve studying the state of preservation of the pollen grains found in soil samples taken from selected contexts, but there are some sources of error that may reduce the method’s validity, so this will necessitate input from botanists.

The application of soil micromorphology may also be an approach that proves to be useful. However, one cannot escape the fact that the result of increasing the number and complexity of analyses intended to make state of preservation assessment a more objective process will be to drive up the cost of archaeological investigations substantially, and this is a matter that Riksantikvaren will have to give careful consideration.

Figure 5.13 The chain of ruined stone buildings at the rear of Dreggen and of Bryggen’s northern end.  
Map: NIKU, Modified by O.M. Hansen, Alkymi Design.





# 06

## PRESERVATION CONDITIONS AND DECAY RATES

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INTRODUCTION

How are ‘preservation conditions’ linked to ‘state of preservation’ and ‘decay rate’?

The terms ‘state of preservation’ and ‘preservation conditions’ on archaeological sites are sometimes used synonymously. However, as stated in the Norwegian monitoring standard<sup>113</sup>, it is necessary to distinguish between the two terms (Fig. 6.1). The state of preservation is the current state of the archaeological deposits including artefacts, ecofacts, structures and soil stratigraphy, as described by Dunlop in chapter 5. The state of preservation depends on both current and historical decay, and the ‘decay rate’ indicates how fast the state of preservation decreases over time. The preservation conditions are the physical, chemical, and microbiological conditions in the ground - in short, the set of environmental parameters - which determine the current decay rate of the archaeological deposits, as discussed in this chapter.

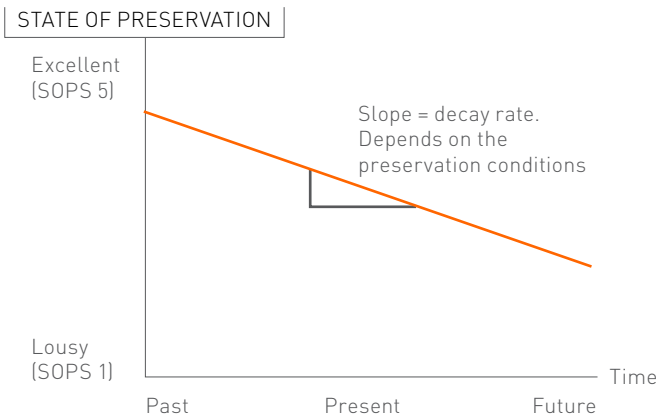


Figure 6.1

Figure 6.1 Illustration of “state of preservation” vs. “preservation conditions” and “decay rate”. Time scale (x-axis) is artificial. The “state of preservation scale” (y-axis), where each archaeological layer or sample is ascribed a value from 1 to 5, is described by Dunlop in chapter 5. From Matthiesen 2014a.

Decay may follow different patterns over time<sup>114</sup>: In Fig. 6.2 the blue line represents a site, an area, or an archaeological material that decayed significantly immediately after deposition, after which it became more stable. The red line represents a site where the decay is gradual and more or less constant over time. The green line represents a site where the decay is extremely slow and the state of preservation is excellent even after centuries or millennia. Finally, the black line represents a site that enjoyed an excellent state of preservation until recently, but then the conditions changed and the decay rate increased significantly. This means that the ‘state of preservation’ and the ‘preservation conditions’ are not always identical - it is possible to have a good state of preservation and poor preservation conditions, or vice versa. In order to ensure continued preservation and prioritize mitigation measures, it is necessary to be able to distinguish between these different scenarios, between past and ongoing decay, and between relatively stable sites and sites under rapid decay. In terms of mitigation work the highest priority should be given to the ‘black line scenario’, i.e. where a site, area or material is still in a good state of preservation, but is undergoing rapid decay.

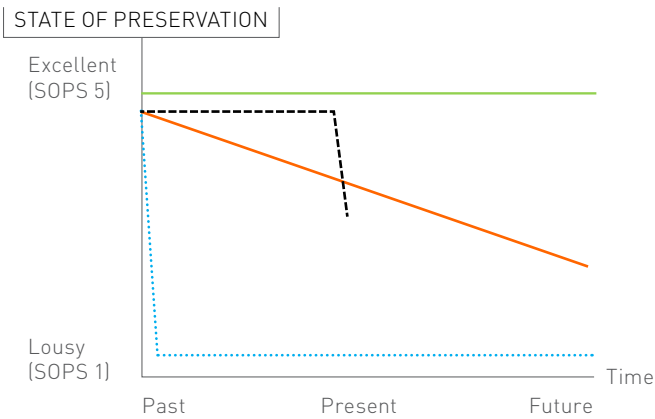


Figure 6.2

Figure 6.2 The change in “state of preservation” over time may follow different paths, due to different site-formation processes and preservation conditions. From Matthiesen 2014a.

Methods to evaluate decay rates

Quantification of decay rates is necessary in order to estimate if a site (and materials therein) is likely to survive for centuries, decades or only a few years. Such estimates are especially important when comparing different sites, different parts of a site, or different threats. A single site may be exposed to several different threats, and in order to prioritize mitigation measures it is necessary to evaluate the effects of each individual threat and determine if all are equally important. It can be difficult to discover and quantify ongoing decay as archaeological sites and materials are often heterogeneous and have been subject to long-lasting site formation processes. For this reason, three different approaches to studying decay have been used at Bryggen from the very beginning of the monitoring project<sup>115</sup> - Fig. 6.3:

- 1. Investigate and quantify the state of preservation of the deposits at regular intervals
- 2. Monitor environmental parameters and use an interpretation scheme to estimate decay rates
- 3. Make model experiments of decay processes in the field and in the laboratory

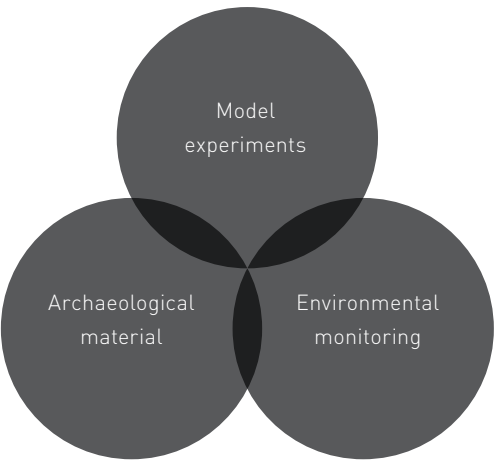


Figure 6.3

Figure 6.3 Several approaches may be used to study decay at an archaeological site. A combination of different approaches is often necessary to evaluate and quantify ongoing decay. Modified from Matthiesen 2014a.

There are advantages and disadvantages to each approach in terms of reliability (i.e. how well it represents the preservation of archaeological remains in situ) and sensitivity (i.e. how fast it can reveal whether there are preservation problems or not). However, by combining all three approaches, it is possible to compare the results and obtain a more robust understanding of the decay at Bryggen. There has been a continuous focus on validating the results, i.e. to compare the predicted decay with long-term observations of changes at the site as described in chapter 5.

Parameters controlling decay

The archaeological deposits at Bryggen are highly organic, and some layers consist of up to 70 % organic material (measured as the weight loss when a dried soil sample is ignited at 550°C). The organic material consists of both spectacular artefacts and structures (chapter 2) and of a less spectacular, but highly informative, organic soil matrix. It contains a wide range of components such as wood, bark, twigs, straw, hazelnut shells, moss, bones, insect remains and dung. A few studies have been made specifically on deterioration of wood in the Bryggen deposits,<sup>116</sup> but in most contexts the organic material



Figure 6.4

Figure 6.4 The archaeological deposits at Bryggen have a very high organic content and contain different types of organic matter. Sample from monitoring well MB22 at Schøtstuene. Photo: A. R. Dunlop, NIKU.



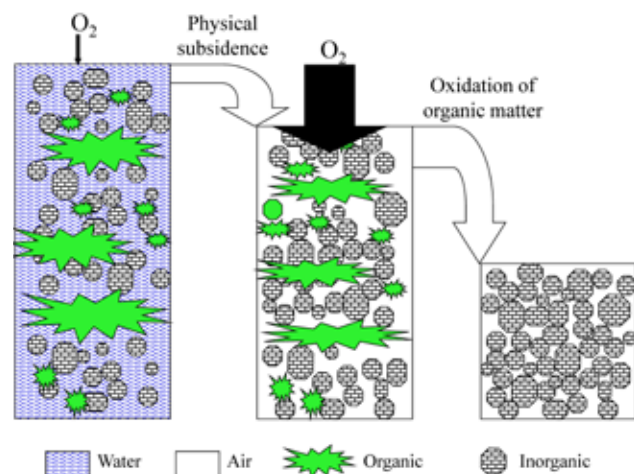


Figure 6.5

is treated as a whole, covering artefacts, ecofacts, and organic soil matrix. Decay of this material not only leads to the loss of archaeological information, but also to a reduction of the soil volume and subsidence of the ground surface and standing buildings (Fig. 6.5), as discussed in detail in chapter 11. The decay rate for organic material in soil is primarily controlled by the supply of different oxidants, the microbial fauna, the temperature, and the reactivity of the organic material itself.

The supply of different oxidants is illustrated in Fig. 6.6. Oxygen is the most reactive natural oxidant and some of the deterioration processes (for instance fungal attack on wood) will only take place if oxygen is available. The supply of oxygen through gas-filled soil pores is much

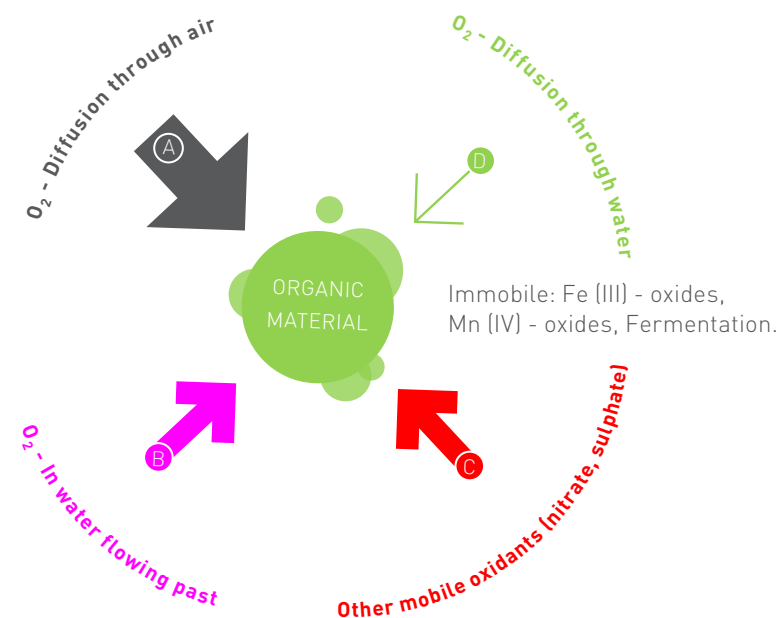


Figure 6.6

faster than through water-filled pores, as the oxygen diffusion constant in air is almost 10,000 times higher than in water. Therefore organic archaeological remains have a much lower chance of survival at drained or unsaturated sites compared to water-saturated sites. However, oxygen is also slightly soluble in water and may be supplied by water flowing through the soil, or by diffusion through still water. Besides oxygen, water may also contain other oxidants such as nitrate or sulphate that can be used by microorganisms to oxidize organic material. These oxidants give a lower energetic output compared to oxygen and will not be utilized before the oxygen is depleted (chapter 7), but their concentration and supply can in some cases be higher. Oxygen, nitrate and sulphate are all mobile and can be continuously supplied

Figure. 6.6 The oxidation of organic material present in archaeological deposits is strongly influenced by the supply of different oxidants. Oxygen is the most reactive oxidant and is supplied through air or dissolved in water. Nitrate and sulphate are both soluble and may be supplied through water. Iron and manganese oxides are solid and immobile, and will only oxidize organic material in their immediate surroundings. Finally, in fermentation the organic material is decomposed without the use of external oxidants. Modified from Matthiesen et al 2008.

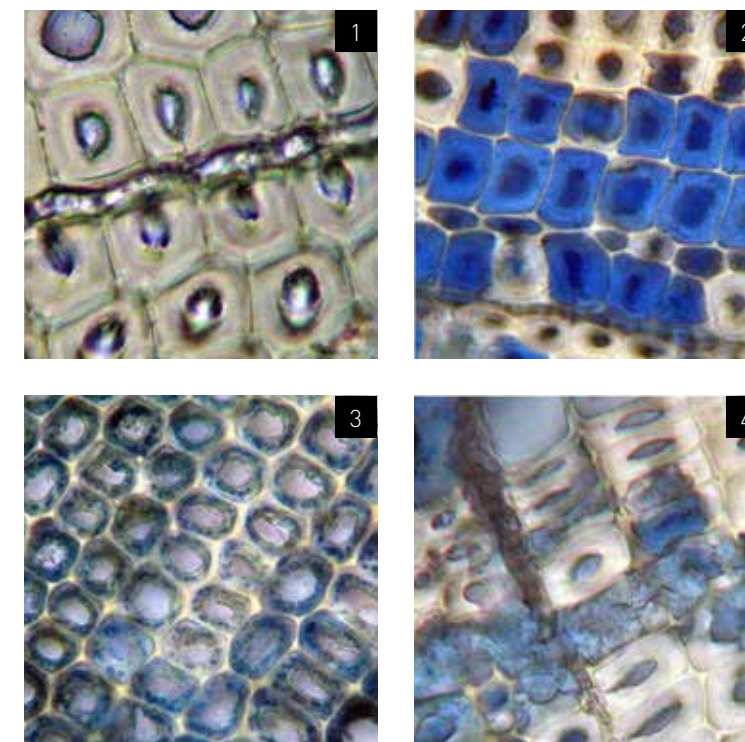


Figure 6.7

to the deposits. However, the deposits also contain immobile oxidants, such as iron oxides and manganese oxides, and some microorganisms can even degrade the organic material through the process of fermentation, which does not require any external oxidants.

The microbial fauna influences the decay rate and decay pattern, and as an example Fig. 6.7 illustrates how different microorganisms give different decay patterns for wood. The most severe and fast decay is caused by oxygen-requiring white rot fungi that may destroy the wood cells completely, whereas other microorganisms only attack specific parts of the wood cells. Different microorganisms may be latently present in the deposits, but their activity is largely controlled by the environmental parameters.

Figure 6.7 Examples of decay patterns for wood samples from Bryggen: 1) fresh piece of wood; 2) decay by bacteria, blue colour indicates decayed wood material; 3) decay by soft rot fungi; 4) decay by white rot fungi. White rot can lead to complete destruction of the wood, while soft rot and bacteria only attack specific parts of the wood cells, allowing the external form of the wooden artefacts to be preserved. Soft rot and white rot are dependent on oxygen, while bacterial decay can also take place under anoxic conditions, albeit at a low rate. Photos: D. Gregory Nationalmuseet. Modified from Gregory et al 2009.

Temperature also influences the decay rate. Both chemical and microbial reactions are temperature dependent, and several studies have shown that the decay rate of organic material in soil increases exponentially at increasing temperatures if no other rate-limiting factors (such as the supply of oxidants) are present. The exponential increase has an upper limit, as the microorganisms fail to grow if the temperature gets too high.

Finally, the decay rate is influenced by the reactivity of the organic material itself, since differences in the chemical composition and physical structure determine how 'attractive' it is to microbial decay. Normally the most reactive components will decay first, and the less reactive components will survive for a longer time.

Some of these parameters are possible to influence through different mitigation measures, others are impossible to control - for instance, the supply of mobile oxidants may be influenced by controlling the groundwater level and water flow through the deposits, whereas it is more difficult to influence, for instance, the reactivity of the deposits.

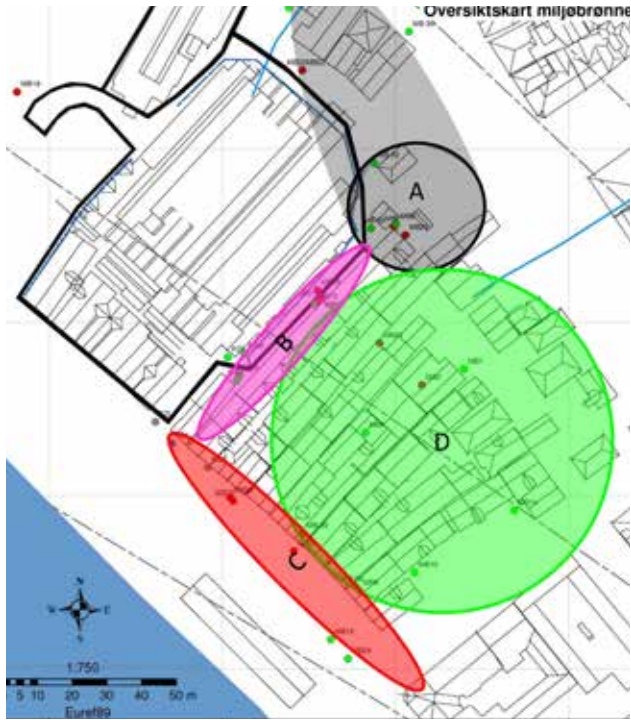


Figure 6.8



Figure 6.9

### Map of Bryggen

The first years of monitoring at Bryggen allowed us to divide the site into four separate areas with different preservation conditions and threats/challenges<sup>117</sup> (Fig. 6.8). These areas are used in the remainder of this chapter to illustrate the effects of different oxidants and supply channels. Area A was characterized by a lowered groundwater level, which may illustrate the effects of oxygen supply through soil air (arrow A in Fig. 6.6). Area B was characterized by an increased water flow through the deposits, where focus was on the supply of dissolved oxygen (arrow B in Fig. 6.6) and other dissolved oxidants (arrow C). Area C was characterized by occasional flooding with seawater, where focus was on supply of dissolved sulphate (arrow C in Fig. 6.6). Finally area D was characterized by a limited groundwater flow, where

focus was on slow diffusion processes and on the effects of fermentation and immobile oxidants (arrow D and immobile species in Fig. 6.6).

## PRESERVATION CONDITIONS ABOVE THE GROUNDWATER LEVEL

Area A was characterized by a low groundwater level and high subsidence rates [chapter 4]. The monitoring above the groundwater level focused on the penetration depth of oxygen into the unsaturated soil layers, and its correlation to decay, soil moisture and precipitation. It was necessary to test new types of oxygen sensors and monitoring

Figure 6.8 Overview of the Bryggen area, where different colours show areas with different preservation conditions and threats to preservation. Modified from Matthiesen et al. 2008.

Figure. 6.9 Jørgen Hollesen installing sensors for measurement of oxygen, soil moisture and temperature in the upper soil layers behind the Bredsgården tenement. Photo: H. Matthiesen, Nationalmuseet.

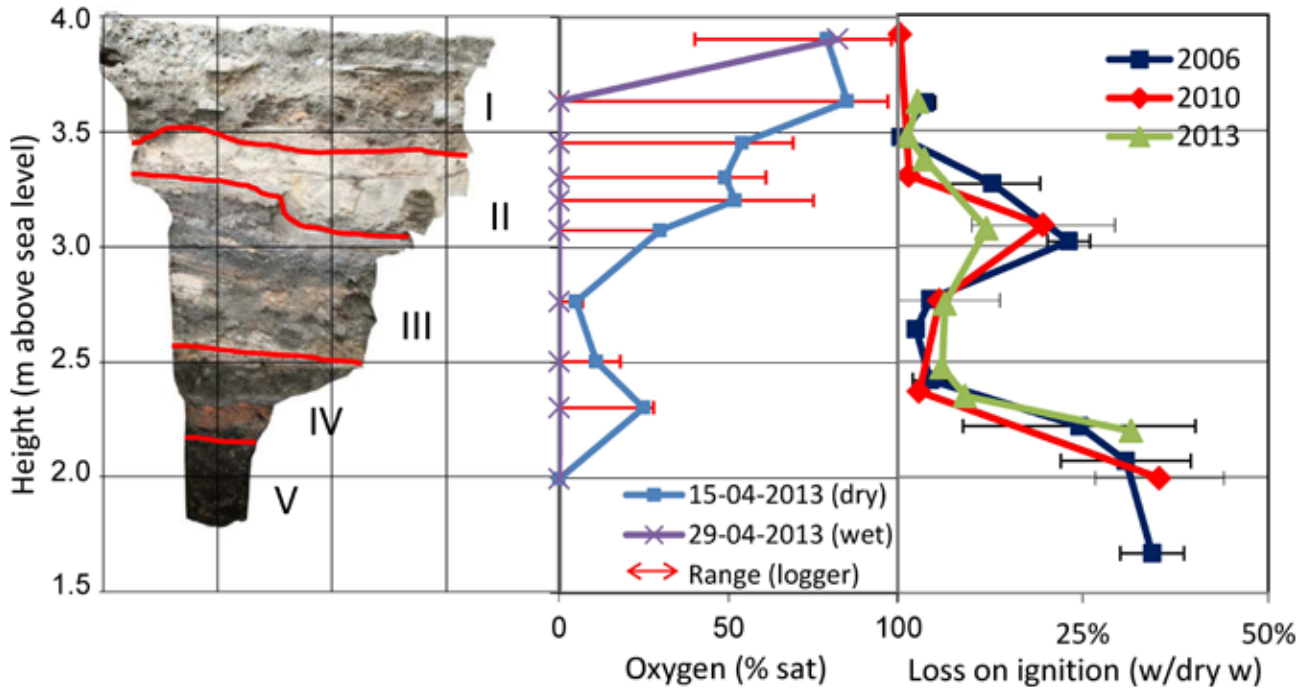


Figure 6.10

systems, as prior to the Bryggen project there was very little experience with monitoring oxygen dynamics in archaeological deposits.

### Monitoring setup

A small test-pit was excavated just to the rear of the northern Bredsgården tenement in 2006 and reopened in the autumn of 2010 in order to install monitoring equipment in the area with severe subsidence problems (Fig. 6.9). The excavations and description of the different soil layers were carried out by archaeologist Rory Dunlop (chapter 5). The archaeological description distinguished between 14 different layers and phases in the test-pit, but based on the soil characteristics this was condensed into five main layers (Fig. 6.10).

Sampling and monitoring in the test-pit was described in detail in different reports and papers<sup>118</sup> During the excavations in 2006 and 2010 soil samples were taken from all soil strata to measure the water content, organic content and soil porosity. Samples of modern pine wood were placed in different soil strata in 2006 and retrieved during the excavation in 2010 in order to study the presence and activity of wood-decaying fungi and bacteria. In 2013 auger drilling was carried out next to the test-pit to retrieve soil samples for renewed analysis of loss on ignition.

The monitoring equipment installed at different depths in the test-pit included 10 oxygen sensors, 5 water content sensors, and 9 temperature sensors. All sensors were connected to a data logger that was programmed to log every half hour. Precipitation was measured in a rain gauge close to the test-pit.

Figure 6.10 Photo from the test-pit with approximate layer boundaries; soil surface is at 4.14 m above sea level (left). Examples of oxygen measurements during dry and wet periods, along with the range measured at different depths over the whole monitoring period (middle). Loss on ignition values measured in samples from excavations in 2006 and 2010, and from a drilling in 2013 (right). Error bars on the loss on ignition data show the standard deviation between duplicate samples from the same layer. Photo: M. Gładki, PAST S.C. Modified from Matthiesen et al. 2014b.

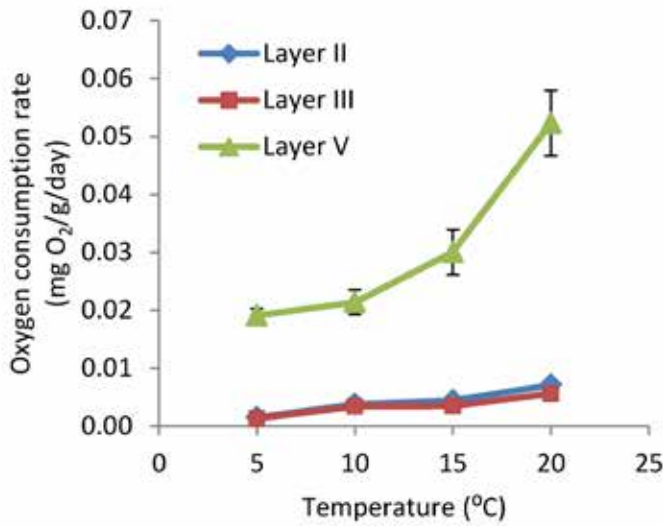




Figure 6.11

The reactivity of the archaeological material taken from the test-pit was measured under controlled conditions in the laboratory.<sup>119</sup> Samples were placed in closed vials and their oxygen consumption was quantified at varying water contents (from 30 % vol to saturated) and varying temperatures (5, 10, 15 and 20°C). After this, the vials were filled with water and the consumption of different dissolved oxidants (oxygen, nitrate and sulphate) was quantified.<sup>120</sup> The oxidants may be consumed by different processes in the soil, but it was assumed that most of it was used by microorganisms for oxidizing organic material, making it possible to calculate a theoretical loss of organic material from the consumption of oxidants.

Figure 6.11 Measurements of oxygen consumption in soil samples from Bryggen under controlled conditions in the laboratory. The samples are placed in airtight containers where the oxygen concentration is followed over time (left). The results show that all samples have increasing reactivity at increasing temperatures, and also that samples from deeper layers in the test-pit (layer V) are significantly more reactive than samples from higher in the test-pit (right). Error bars show standard deviation for triplicate samples. Modified from Hollesen & Matthiesen 2014.



## Results prior to mitigation work:

### Laboratory studies of decay

Laboratory studies of soil samples from the test-pit showed that the soil temperature had a significant effect on the decay, and that a 10°C temperature rise increased the decay rate of the analysed samples by 100-180 % (Fig. 6.11).

Both microbial and chemical reactions are temperature dependent, and a 2-3-fold increase in reaction rate for a 10°C temperature rise is not unusual. Thus, the temperature effect is so significant that it should be included in the evaluation of preservation conditions. Increased soil temperatures are frequently found at urban sites due to heating of buildings and cellars, subsoil infrastructure such as district-heating pipes, dark surfaces such as asphalt, and a relative dearth of cooling and shading plants and trees. Locally increased soil temperatures have also been documented at Bryggen, especially along the sheet piling (chapter 7 and 8). The laboratory studies also showed that the decay rate depends on the soil moisture and that it is lower under both very wet and very dry conditions.<sup>121</sup> The wet conditions are discussed in more detail below, whereas the lowered decay rate under very dry conditions is of little practical use at the Bryggen site, as dry conditions have other negative effects on the archaeological material.

Furthermore the results showed that different soil samples have different reactivity, and for instance that soil material from saturated, anoxic conditions is much more reactive compared to material that has been under oxic conditions for a prolonged period. Different components in the soil material have different reactivity and the microorganisms will typically use the most reactive and accessible material first. Given this large variation, it is necessary to evaluate the reactivity of any particular archaeological deposit before estimating the vulnerability and decay rate in situ.

Finally, the measurements documented and quantified the different reactivity of different oxidants, as described in the previous section. The highest decay rates were measured in unsaturated soil samples with good oxygen access, high rates were also measured in saturated soil samples with dissolved oxygen or nitrate, whereas the rates in saturated soil samples with dissolved sulphate were approximately ten times lower (but still unacceptably high).

### Oxygen penetration depth and comparison to decay in situ

Measurements showed that the ground surface in area A was subsiding and it was quickly hypothesized that the subsidence was due to decay of organic material in the archaeological deposits (Fig. 6.5). However, in order to plan mitigation work it was necessary to find out in exactly which soil layers the decay took place, and also whether it took place all year round or only in some periods.

The conditions in the unsaturated zone turned out to be very dynamic, with oxygen concentrations and water contents varying considerably from day to day in close correlation with the precipitation.<sup>122</sup> Some general trends in the oxygen distribution and variation are presented in Fig. 6.10 (middle). During the monitoring period oxygen was permanently or at least very frequently present in the upper 1 m of the test-pit (layer I and II), it was seldom present and only at very low concentrations in layer III, it was occasionally present at low concentrations in layer IV, and it was never present in layer V. Correspondingly, the wood samples that were installed in the soil layers in the period 2006-2010 showed decay by oxygen-demanding fungi in the soil layers with permanent or occasional presence of oxygen, but only bacterial decay in other layers. Over time, the presence of oxygen can also lead to a decrease in the organic content and loss-on-ignition values of the soil. Fig. 6.10 (right) indicates that the loss on ignition measured at the bottom of layer II decreased

between the repeated sampling campaigns from 2006, 2010 and 2013, even if the results displayed a large uncertainty and wide confidence intervals.

When the in-situ measurements of oxygen, water content and temperature were combined with the laboratory studies of decay, (Fig. 6.11) it was possible to estimate a theoretical decay rate in the different soil layers.<sup>123</sup> This indicated that most decay took place in layer II and occasionally in deeper layers, where there was a combination of frequent oxic conditions and relatively reactive soil. Furthermore, it indicated that the decay took place all year round. The study estimated that prior to mitigation work the annual loss of organic material in the upper 2 m of the test-pit could be up to 1-2 % of the total amount, depending on the model used to interpret the monitoring data.<sup>124</sup>

Overall, these observations gave insight into where and when decay took place. Furthermore it confirmed the prominence of oxygen's role in the decay of organic archaeological deposits and thus the importance of understanding the oxygen dynamics and finding ways of reducing the presence of oxygen.

### Correlation between oxygen and soil moisture

It is well established that the transport and supply of oxygen is greatly influenced by soil moisture, and that the oxygen supply is much faster in dry soil compared to water-saturated soil. However, there is a large range between 'dry' and 'saturated', and the unsaturated zone often contains soil with different degrees of saturation. It was necessary to study this in much more detail in the Bryggen project in order to get a more quantitative measure for 'how wet is wet enough' to reduce the supply of oxygen and keep the deposits anoxic.

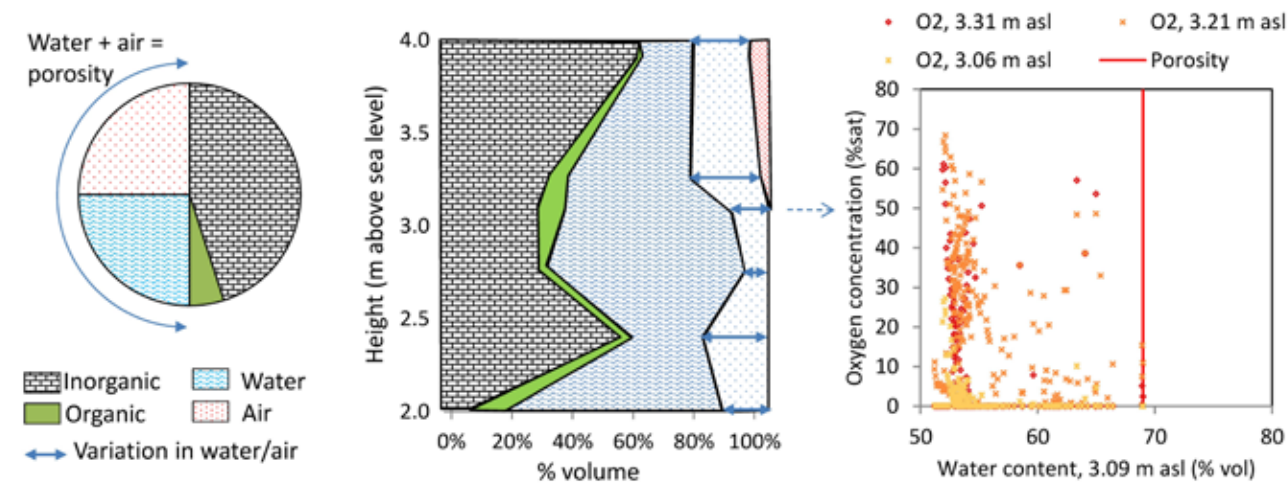


Figure 6.12

The soil porosity is a measure of the pore space in the soil, which is filled with either air or water (Fig. 6.12 left). The porosity of soil samples from the test-pit varied between 40 and 80 % volume, which means that some soil layers were water saturated when they contained 40 % vol water, while others needed 80 % vol water to become water saturated. The water content (and thereby also the air content) of the different layers varied during the monitoring period as indicated by blue arrows in Fig. 6.12 (middle). There was a strong correlation between water content and oxygen content, and it was found that as a general rule oxygen occurred in a given soil layer in the test-pit when the air content exceeded 10-15 % vol.<sup>125</sup> As an example Fig. 6.12 (right) shows results from layer II where the porosity is 69 % vol and where oxygen mainly occurred when the water content dropped to 55 % vol, corresponding to an air content of 14 % vol. The actual oxygen concentration measured will be influenced

by both the oxygen supply and oxygen consumption, and there can be a delay between changes in the water content and changes in the oxygen concentration. Overall, this confirms that the oxygen concentration in the soil is highly influenced by the water content, but also that the water content should always be compared to the soil porosity.

### Effect of wet and dry periods

Water is normally considered beneficial for preservation conditions as the presence of water greatly reduces the diffusive supply of oxygen. However, the water may also contain some dissolved oxygen itself, and it was necessary to evaluate how much oxygen may actually be supplied to the deposits through infiltrating water, and if this could have a negative effect on the preservation conditions. This was especially relevant if water should be actively supplied to the deposits as part of the mitigation measures.

In order to study this it was necessary to look in more detail at what happened when oxygen-rich water infiltrated into the soil. Fig. 6.13 (upper graph) shows an example of oxygen and water-content data from layer II during a precipitation event, where it started raining heavily (70 mm within 24 h) after a prolonged dry period. The data showed a temporary increase in the oxygen concentration at the very beginning of the rain event on the 29th of December, which could be due to oxygen dissolved in infiltrating rainwater. However, as soon as

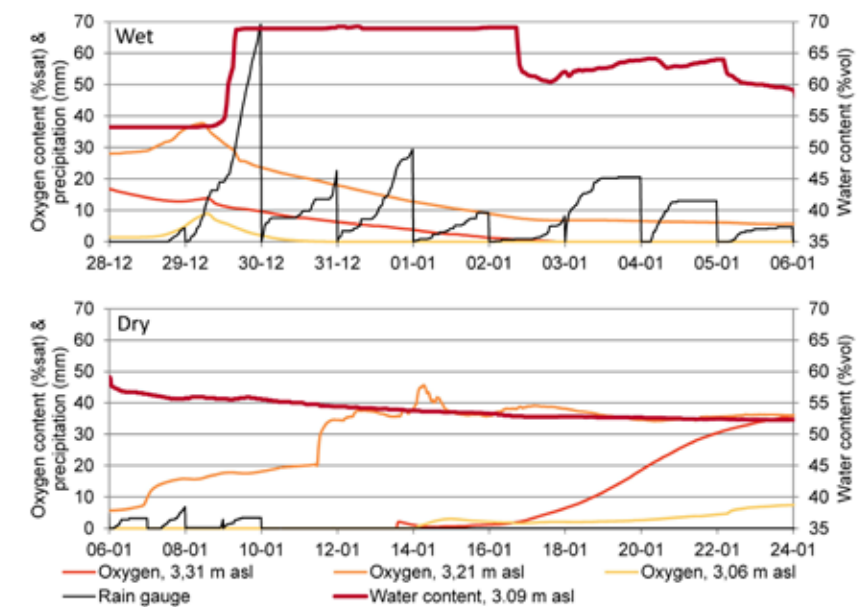


Figure 6.13

the soil moisture content started increasing the oxygen concentration decreased at all depths and the overall effect of the rain was a decrease in oxygen concentration and supply, rather than an increase.

The wet period was followed by a dry period (Fig. 6.13, lower graph). For one of the oxygen sensors (at 3.21 m asl) the concentration started increasing immediately as the water content decreased, whereas it took approximately one week before any oxygen was measured at the two other oxygen sensors (3.31 and 3.06 m asl) in layer II. This difference in oxygen dynamics may be due to local differences in the soil structure, oxygen consumption and water retention (i.e. the ability to retain water by capillary forces).

Overall, this confirmed that the infiltration of water is beneficial and helps to keep the deposits anoxic, even if the water itself may contain a small amount of oxygen.

### Goals for mitigation work

To summarize, the monitoring in the unsaturated zone indicated that: oxygen was present in the unsaturated soil layers, especially during dry periods; -this resulted in decay of organic material in the soil which may explain the observed subsidence; - in the test-pit the decay mainly took place in the upper soil layers and down to approximately 1½ m below the ground surface; -the oxygen supply was reduced when the soil layers were more wet; and oxygen dissolved in infiltrating (rain) water was quantitatively of less importance. Based on these observations it was evident that mitigation methods should focus on increasing the soil moisture and the groundwater level, by reducing the drainage and increasing the infiltration of water (chapter 8-10). Flooding and waterlogging all soil layers was not possible, nor was it desirable, as it may have negative consequences for the buildings. Instead, the goal was to increase the soil moisture sufficiently to obtain anoxic conditions from a few decimetres below the ground surface and downwards.<sup>126</sup>

### Effects of mitigation work

The effects of the mitigation work were checked by measurements of subsidence, the groundwater levels, the soil moisture, and the oxygen content in the unsaturated zone. The subsidence has been reduced and the groundwater level increased, as discussed in chapters 8 and 11. As for soil moisture in the unsaturated zone, some soil layers now show shorter periods with low water

Figure 6.12 The pore space between the soil particles is called the soil porosity, and these spaces are filled with air and/or water (left). Different types of layers in the test-pit have different porosities, and the ratio between water and air may vary considerably over time and space (middle) - the air content cannot be measured directly but is calculated as porosity minus water content. Comparison between oxygen and water content measurements in layer II shows that oxygen concentrations typically increase when the water content drops below a certain level (right). Modified from Matthiesen et al. 2014b.

Figure 6.13 Example of temporal variations in oxygen concentration and water content in layer II during a wet (upper graph) and a dry (lower graph) period from December 2012 to January 2013. Precipitation data from the rain gauge are shown cumulatively for each 24h period, based on measurements every 15 minutes. From Matthiesen et al. 2014b.



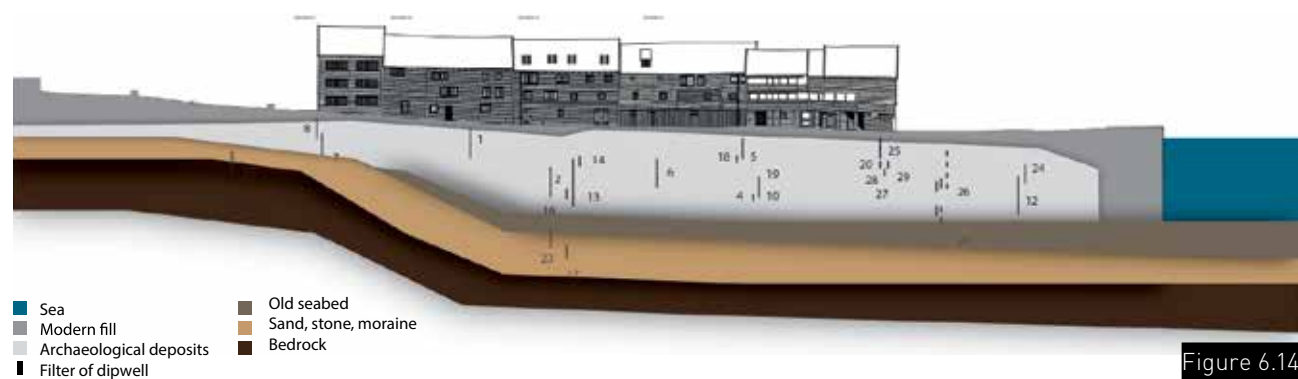


Figure 6.14

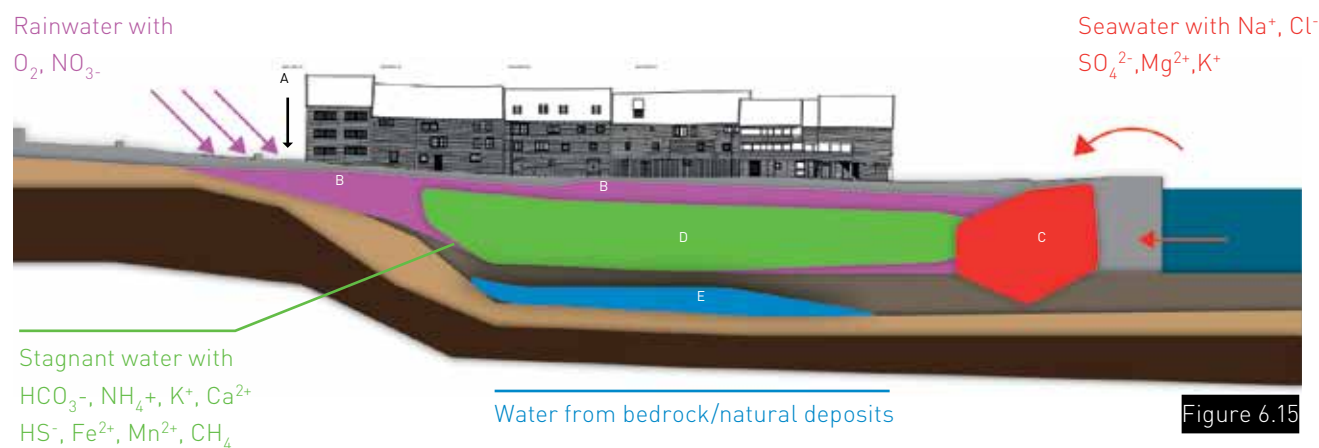


Figure 6.15

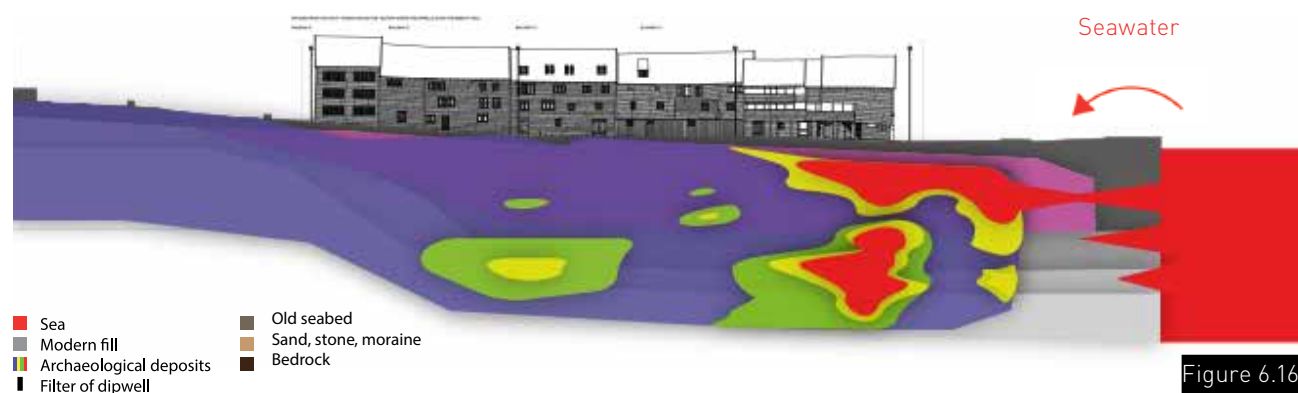


Figure 6.16

Figure 6.14 Monitoring wells were installed all over the Bryggen area, with their water intakes (filter) at different depths and in different soil strata, in order to monitor the level and chemical composition of the groundwater. Modified from Matthiesen 2008. Modified by O.M. Hansen, Alkymi Design.

Figure 6.15 Conceptual model of hydrogeology and groundwater chemistry. The detailed analysis of groundwater from 40+ monitoring wells showed some general trends in the water chemistry that allowed us to distinguish between different sources of water and between good and poor preservation conditions. A: localized area with lowered groundwater level at the rear of Bryggen (not shown in this cross-section); B: contribution from rainwater; C: contribution from seawater; D: the contribution from old stagnant water. Modified from Matthiesen et al. 2008.

contents, but the natural variation is extremely large and it is difficult to quantify the effect yet, as the infiltration systems at Bryggen have only been in use for less than a year. As for the oxygen content in the soil, some of the deeper layers now show longer periods with anoxic conditions, but again the natural variation in the previous years has been extremely high, and it is too early to give quantitative estimates of the effect. The full effect of the mitigation work can first be evaluated after a longer period, which should also include some dry periods with no precipitation.

## PRESERVATION CONDITIONS BELOW THE GROUNDWATER LEVEL

In areas B, C and D (Fig. 6.8) the focus has been on the groundwater quality and how the chemical composition of the water may influence the decay of archaeological material. In order to estimate this it is necessary to have detailed information about the supply of water, the concentration of different species dissolved in it, and the reactivity of these species. This has required the coupling of the chemical analyses of the water with a hydrological model and laboratory studies of decay under water-saturated conditions.

### Monitoring setup

A total of 48 monitoring wells have been installed across the Bryggen area between 2000 and 2014, with their filters (water intakes) at different depths and in different deposits (Fig. 6.14). The monitoring wells are used to measure groundwater levels and temperature (chapter 8), and for taking samples of the groundwater for analysis of its composition. Samples were taken from each well a

Figure 6.16 Chloride content of the archaeological deposits, interpolated from the results of 150 soil samples. Red colour shows chloride contents above 3500 mg/L, and purple shows contents lower than 700 mg/L. The quayfront is occasionally flooded with a mixture of seawater and rainwater. From Matthiesen 2010b.

few weeks after their installation, and on three occasions (in 2005, 2008 and 2011) samples were taken from all wells at the same time. The samples were analysed in the laboratory for a range of different parameters, which has given a good overview of the groundwater composition in different parts of Bryggen (Fig. 6.15). This was supplemented by automated loggers (multiparameter probes) that made continuous measurements of oxygen concentration and other parameters within selected monitoring wells.

Samples of modern wood were placed in the soil<sup>127</sup> and in selected monitoring wells<sup>128</sup> for 1-2 years before they were retrieved to study their state of decay.

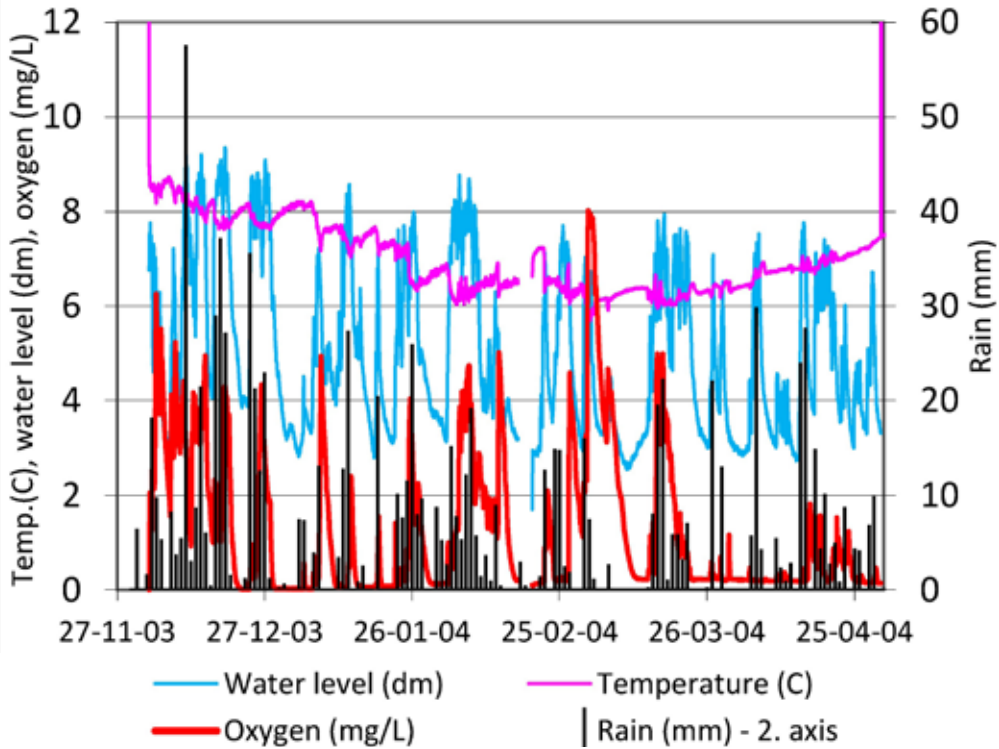
The reactivity of the deposits towards different dissolved species was studied under controlled conditions in the laboratory. Samples from water-saturated deposits were placed in vials, which were filled with a buffer solution (similar to groundwater from Bryggen) and closed with an airtight seal. Different oxidants such as oxygen, nitrate and sulphate were added to the vials, and the reactivity was evaluated by measuring how fast the oxidants disappeared.<sup>129</sup>

## Results prior to mitigation work

### Area B - increased water flow

The area alongside the sheet piling was investigated in terms of horizontal and vertical water flow and its consequences for the preservation conditions. The horizontal water flow in the upper deposits was significant in the area, causing very dynamic conditions and flow of oxygen-rich water through the deposits (pink arrow in Fig. 6.6). As an example Fig. 6.17 shows measurements of oxygen, water level and temperature in one of the monitoring wells (MB5) in the area. The oxygen logger was placed within the well's filter length at -1.4 m asl, where oxygen measurements carried out directly in the soil had previously shown increased oxygen content. The measurements from 2003-04 (Fig. 6.17:1) revealed an extremely dynamic environment, where the water level and oxygen concentration increased abruptly every time it rained, and decreased quickly after the rainfall stopped. This showed that oxygen-rich rainwater could actually reach considerable depths in the deposits in this area close to the sheet piling, probably because the sheet piling served as a barrier that diverted the groundwater flow. The solubility of oxygen in water is relatively low

Figure 6.17:1



(only 12 mg oxygen may dissolve in 1 L of water at 7°C), but with a sufficiently large water flow the oxygen supply may still be significant. Rainwater may also contain some nitrate (a few mg/L), which contributes to oxidation of organic material (Fig. 6.6, red arrow). The conditions in the deeper deposits near the sheet piling were not as dynamic as in MB5, but still the groundwater chemistry was characterized by an increased dilution with rainwater compared to the more stagnant area D.<sup>130</sup> Furthermore, temperature measurements showed heating of the deposits near the sheet piling (chapter 7).

In order to document the possible effects of the increased water flow, model experiments were carried out in the field and in the laboratory. Modern wood samples placed in monitoring wells and in a test-pit next to MB5 showed fungal decay in areas with an increased water flow and

occasional occurrence of oxygen. Laboratory experiments with Bryggen samples showed that the presence of oxygen gave increased decay rates under both saturated and unsaturated conditions.<sup>131</sup>

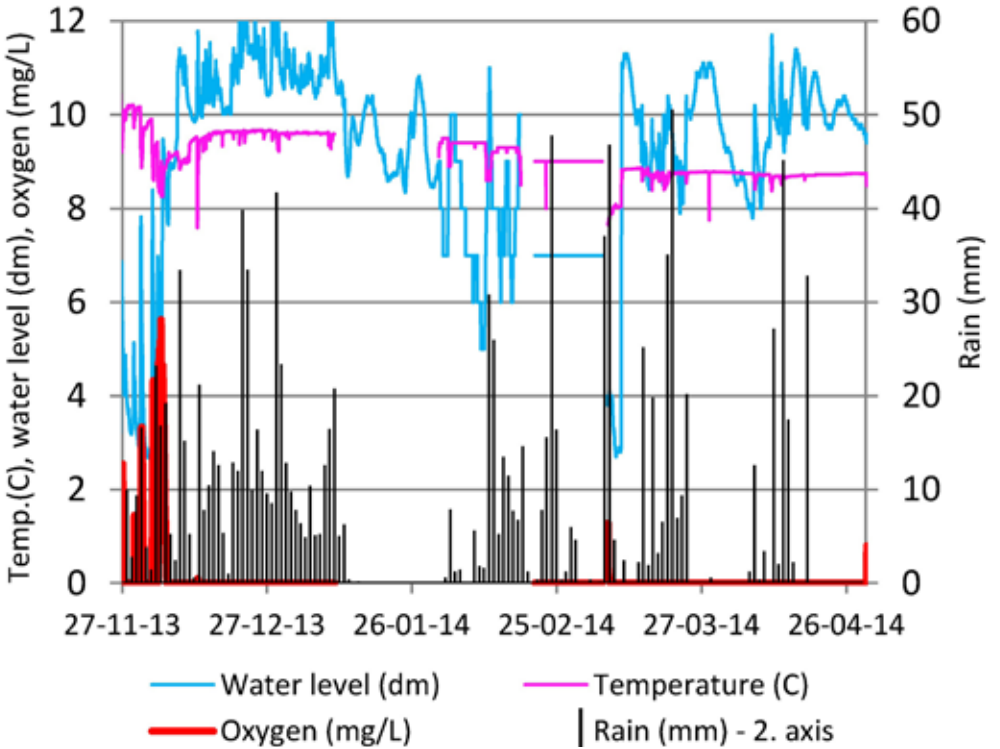
It has proved difficult to determine the exact decay rates along the sheet piling, as the flow rates and flow paths were uncertain. A preliminary geochemical model was made, according to which it was estimated that there was an annual loss of up to 1 ‰ of the organic material in the deeper deposits near the sheet piling,<sup>132</sup> while the loss in the upper deposits was probably greater. In connection with this, it should be noted that Dunlop was able to detect that the state of preservation of some of the deep deposits near the sheet piling had deteriorated from excellent to good during the monitoring period from 2005 to 2009 (chapter 5 – comparison between MB13 and MB15).

**Area C - flooding with seawater**

The area along the quayfront was investigated in terms of seawater intrusion and its possible consequences for preservation conditions. Seawater contains high concentrations of different ions, including chloride (19 g/L) and sulphate (2.7 g/L). The concentration of chloride was measured in more than 150 soil samples (Fig. 6.16),

Figure 6.17:1-2 Continuous logging of water level, oxygen concentration, and temperature in groundwater in monitoring well MB5, close to the sheet piling. Fig. 16.17:1 shows data from winter 2003-04 and Fig. 16.17:2 shows data from the same period in winter 2013-14. There are some gaps in the data series from 2013-14 due to construction work taking place around MB5. Illustration: H. Matthiesen, Nationalmuseet.

Figure 6.17:2



which showed a clearly higher concentration at the harbourfront. Chloride may increase the corrosion of iron, but is not a factor in organic decay. Sulphate from the seawater, on the other hand, may well contribute to the decay of organic materials (red arrow in Fig. 6.6). To estimate its importance it was necessary to study both the reactivity and supply of sulphate.

Model experiments in the laboratory showed that the reactivity of sulphate was significantly lower than the reactivity of nitrate and oxygen.<sup>133</sup> Still, the reactivity of sulphate was high enough to give a significant and unacceptable decay over time if there was a continuous supply of new sulphate. It was thus necessary to study the supply in situ.

Before the mitigation work the quayfront was typically flooded a couple of times per year with a mixture of seawater and rain,<sup>134</sup> and during high tide some inflow of seawater took place as backflow through sewage pipes. However, it was unknown to what extent this seawater infiltrated into the archaeological deposits. An intensive sampling campaign was carried out, where groundwater samples were taken from monitoring wells along the quayfront every 2-6 weeks for half a year to study

the variations in sulphate and chloride.<sup>135</sup> The results indicated that there were dynamic conditions and a frequent supply of sulphate in the upper, porous deposits in front of the buildings, whereas in the deeper and more compact deposits below the seaward gables the supply of 'fresh' sulphate was more limited. No new flooding occurred during the intensive sampling campaign, so the effects in the deeper deposits may be underestimated. The decay rate in situ was difficult to determine due to uncertainty concerning the sulphate supply, but the annual loss of organic material in the deposits in front of the buildings probably lies between 1 ‰ and 1 ‰, with lower rates below the front buildings.<sup>136</sup>

**Area D - stagnant anoxic groundwater**

The central part of Bryggen was characterized by a high groundwater level and relatively stagnant conditions - the downward rate of water flow has been estimated to be between 0.1-1 m/year. This is considered close to optimal conditions and the monitoring focused on understanding the groundwater-formation processes.



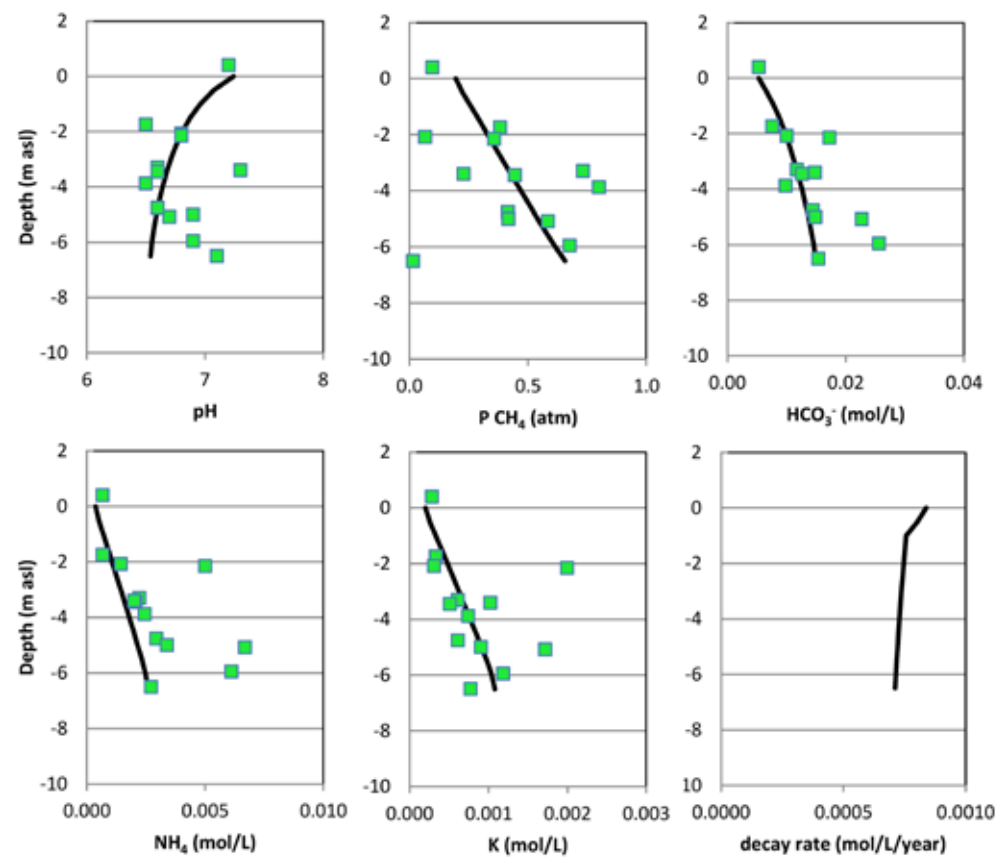


Figure 6.18

From sampling of the large number of monitoring wells it was realized that the groundwater composition showed some distinct correlations between different ions in the water.<sup>137</sup> In the central area the concentrations of, for instance, ammonium, potassium, bicarbonate and methane increased with depth (Fig. 6.18), and it was realized that this could be due to interaction between water slowly percolating downwards and the immobile soil material. Mobile oxidants such as oxygen, nitrate and sulphate are used up in the uppermost soil layers. Regarding the immobile oxidants, the most reactive iron and manganese oxides were probably reduced in these organic archaeological deposits centuries ago. The decay process in the deeper deposits therefore becomes dominated by the (very slow) fermentation that produces methane and carbon dioxide/bicarbonate. Based on a hydrochemical modelling of the processes, it was estimated that the decay rate of the organic material is

exceedingly slow and that the deposits may stay in an excellent state of preservation for thousands of years, if conditions do not change. The annual loss of organic material was estimated as low as 0.1 ‰ of the total amount, depending on the groundwater flow rate.<sup>138</sup> The estimated rate has not yet been documented through laboratory measurements or simulations, as it is quite difficult to study such slow processes in 'real time'.

The preservation conditions in this area are probably as good as they can possibly be and the estimated decay rates may serve as a benchmark for other areas within the Bryggen WHS, as well as for other archaeological sites.

### Goals for mitigation work

Based on the monitoring results and estimated decay rates, the goal for area B was to reduce the water flow along the outside of the sheet piling so as to obtain more stagnant conditions. In area C, the goal should be to decrease the frequency of flooding even further, if possible, both to reduce the infiltration of sulphate-rich water and to protect the buildings. The conditions in the central part of Bryggen (area D) should remain unchanged during and after the mitigation works.

### Effect of mitigation work

Barriers made of bentonite clay have been placed at various points along the sheet piling as described in chapter 8. This - together with other mitigation measures - seems to have reduced the transport of oxygen through the deposits significantly at MB5. Fig. 6.17 shows how oxygen was present in MB5 frequently during the winter of 2003-04 (Fig. 8.17:1), whereas in the winter of 2013-14 (Fig. 8.17:2) there were only a few days when oxygen was present. As for the situation in other monitoring wells along the sheet piling, the groundwater chemistry is checked by taking samples every two months in order to see if conditions become more stagnant. The development from 2012-2014 is very promising, but it is too early to say anything final about the effects, as the mitigation work has just recently been finished and it may take several years before the groundwater chemistry achieves a new steady state.<sup>139</sup>

The sewage system at the harbourfront (area C) has been changed, and non-return valves have been placed in the sewage pipes to prevent influx of seawater at high tide. This has reduced the number of flooding events significantly, to the benefit of the front buildings. The effects in the soil have not yet been investigated.

As for the central area (D), groundwater sampling still indicates very good preservation conditions and no negative effects connected to the mitigation work at Bryggen have been observed. The conditions within the whole Bryggen area will be followed in the future by sampling all monitoring wells every 3-4 years.

## CONCLUSIONS

The use of several approaches to study decay (Fig. 6.3) has proven very useful at Bryggen. It requires a high level of collaboration and data-sharing between the different partners in the monitoring work, which has worked out perfectly in the Bryggen project. The monitoring has been quite comprehensive in order to document preservation conditions and estimate decay rates in different areas. The preservation problems were thus well documented before mitigation work was initiated. The mitigation work has already had clear effects in some areas, but it will probably take several more years before the full effect can be documented - with a volume in excess of 100.000 m<sup>3</sup> the archaeological deposits at Bryggen represent a large 'system' and it takes a long time before

such a system enters a new steady state in terms of soil moisture, groundwater level and, not least, groundwater chemistry.

Some of the knowledge achieved at Bryggen can be directly transferred to other sites. For instance, Bryggen was the first site where oxygen has been monitored in archaeological deposits for a prolonged period, which has yielded much more knowledge about oxygen dynamics. The equipment used has been stable and produced reliable results for several years, and one has no hesitation in recommending installation of similar equipment at other sites to get more experiences from different deposits. The use of model experiments and laboratory measurements of decay have proven very useful for interpreting the monitoring data. In addition, the effects of temperature on the decay rate (Fig. 6.11) is highly relevant not only at urban sites, but also at other sites where average annual temperatures in the soil may increase due to climate change.<sup>140</sup>

For the saturated zone, the comprehensive groundwater analysis and the combination of hydrogeological and geochemical modelling have been fruitful. It has given an improved understanding of the complex processes going on in the deposits, and this can be turned to the interpretation of data from other sites. The study of effects of different types of water may be used to set quality requirements concerning water used for infiltration, and also to predict effects of increased seawater intrusion due to sea-level rise. Finally, the very low decay rates estimated for the central part of Bryggen may be used as a benchmark for other sites.



# 07

TEMPERATURE, REDUCING  
AND OXIDIZING CONDITIONS

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Michel Vorenhout  
MVH Consult



## WHAT IS MEANT BY ‘REDOX POTENTIAL’?

The decay of the organic components of the Bryggen foundations is highly dependent on the availability of oxidants like oxygen. The water content in the soil governs the availability of oxygen for the microorganisms that live in the soil and use this oxygen in the process of consuming the wooden and other organic parts of the archaeological heritage: they eat up the archaeology! Consumption of organic matter in the soil - a normal process in nature - is the principal cause of the subsidence that occurs at Bryggen. During this consumption, the microorganisms need the oxygen to store the excess electrons deriving from the decay of the organic matter.<sup>141</sup>

When oxygen is present, the possible speed of decay is highest, as oxygen represents the easiest way to absorb these excess electrons. This process is called aerobic decay. Microorganisms can, however, also use other oxidants, such as iron, nitrate or even organic matter itself, as the electron receptor.<sup>142</sup> When other electron receptors than oxygen are used, anaerobic decay occurs (absence of air). Other words for these conditions are oxidizing, when oxygen is present, or reducing, when electron receptors other than oxygen. The parameter that describes the reduced or oxidized state of the soil is the redox potential.<sup>143</sup>

The measurements of oxygen, as described in chapter 6, have shown that the organic deposits at Bryggen are sometimes oxic, and aerobic decay can occur. The aim of the recent mitigation works at Bryggen is largely to reduce the presence of oxygen in the soil by raising the water table. This will result in very low to zero oxygen levels, levels that cannot be measured. Measurement of the redox potential can provide information on the decay potential in the soils once oxygen is depleted. A high redox potential, mainly with values higher than +400mV, shows an oxic environment, with oxygen present.<sup>144</sup> Low redox potentials, below 0mV, show anoxic conditions.<sup>145</sup> Redox potential values between 0 and 400mV are usually referred to as sub-oxic.<sup>146</sup> Fig 7.1 shows the relationship between the redox potential and the electron receptors that play a role at that redox value. It also shows there is considerable overlap for possible processes in the reduced (<0mV) region of the redox potential scale.

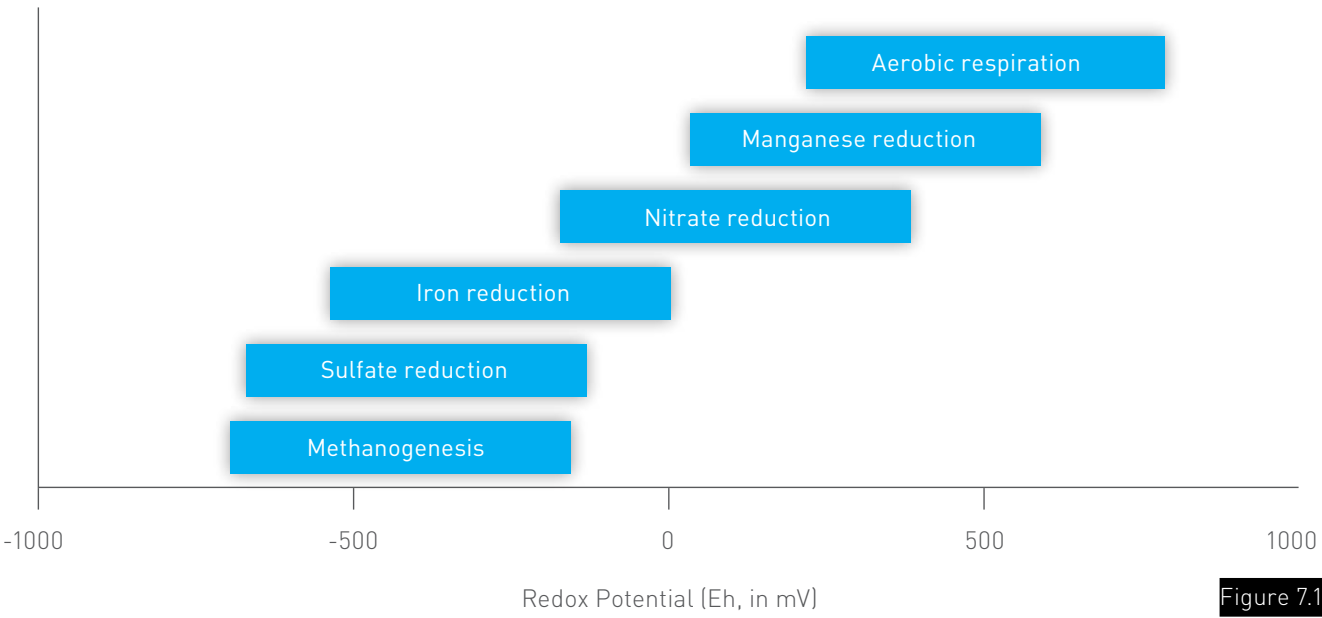


Figure 7.1

### Overlap with oxygen measurements

Redox potential is an integrated parameter of the oxidation/reduction condition of soil or water. It is not as precise as the direct measurement of oxygen. Then why even bother to measure it, why not focus only on the measured oxygen levels? There are two main reasons to include the redox potential in monitoring.<sup>147</sup> First, Fig 7.1 shows that oxygen can only be measured at positive redox potentials; when oxygen is present. Direct measurement of oxygen alone will therefore only provide information on the oxidized soil, and will not be able to follow the anoxic conditions. The second main reason is applicability and cost. Techniques for the measurement of the redox potential in archaeological deposits have been tested and applied for numerous years now, and are in general not more expensive than methods for measuring groundwater level, for instance.

This chapter presents the reasons for and the results of monitoring the redox potential at two locations in Bryggen, and will also discuss temperature as a factor. It will end with some recommendations concerning the monitoring of oxidized/reduced conditions at archaeological sites in urban areas.

## REDOX POTENTIAL VALUES AT BRYGGEN

### Objectives and methods

The general methods for the measurement of redox potential are described in detail by Vorenhout et al 2004 and 2011.<sup>148</sup> In short, one needs a probe with an inert metal in good contact with soil. This probe is the measurement probe. Then, a stable reference value - with a fixed potential, a reference probe - is needed. Both are then connected to a measurement device. Monitoring of redox potential in Bryggen is done by two Hypnos III units (MVH Consult, Leiden, the Netherlands) connected to a range of probes (Paleo Terra, Amsterdam, the Netherlands). The probes were extended in length so they could be installed into small-bore predrilled holes, several metres deep. They were installed in bundles in May 2011. The depths of the platinum tips were matched to either known archaeological strata (known from monitoring well installation), or expected water tables and relevant soil structures. Fig 7.2 shows the bundle of probes that was placed in the narrow boreholes. The holes were created by a drilling rig (Fig 7.3) equipped with a “down-the-hole” or “hammer drill”.<sup>149</sup>

This method of installation is not ideal, but was chosen as it enabled quick installation without an archaeological excavation to create a trench. Forcing the probes down by hand from the surface was not feasible, due to the numerous obstructions (stones, timbers, etc.) in the soil.

Figure 7.1 The relationship between the redox potential values and various chemical processes that can occur. The higher the value for Eh, the more easily the degradation of organic matter occurs. Illustration: M. Vorenhout, MVH Consult. Modified by O.M. Hansen, Alkymi Design.



Figure 7.2

This method is otherwise the preferred option, and has been used in clay and peat soils in the Netherlands, for instance. The pushing method ensures that the probe tip does not end up in an air-filled cavity, and prevents surface water from entering the soil through the artificially made hole. The risk of obtaining poorer-quality data resulting from the lowering of the bundles of probes into narrow pre-drilled holes was considered a fair trade-off. Negative effects on the data can be that they are too variable, and that there is an overestimation of the effect of groundwater-level changes.

Each probe was equipped with a temperature sensor as well, enabling the study of the temperature effects (see chapter 6, Fig. 11). We will first describe the redox potential results, and focus on the temperatures in paragraph Soil temperatures.

### Interpretation

The redox potential was measured semi-continuously at an interval of 15 minutes.<sup>150</sup> This high frequency allows for high-precision interpretation of the effect of groundwater level changes, weather conditions, and possibly other short term effects.<sup>151</sup> Interpretation takes place at two levels: the actual value of the redox potential (Eh),<sup>152</sup> and the changes in those values. The value relates to the oxic, sub-oxic or anoxic conditions in the layers. Each level of redox values corresponds with a certain combination

Figure 7.2 Bundles of the redox potential and temperature probes, as installed at Bryggen.  
Photo: M. Vorenhout, MVH Consult.



Figure 7.3

of possible decay processes. The variation in the values is also of great importance. The more combinations present in the soil, the higher the risk for decay in the longer run, as more types of microbial processes can occur. The general rule of thumb therefore is that stable redox potential values are preferred over variable ones. Interpretation should be done on short (hours to days) and longer (months) time periods. In the case of Bryggen, the major differences in variation and values are related to the time before and after the mitigation measures were put into operation.

### MONITORING RESULTS NEAR SHEET PILING

The measurements near the sheet piling took place at depths down to five metres below the surface. Probes were placed at two distances from the sheet piling, allowing the interpretation of the effects of this barrier. This location was near three dipwells, with MB13 being the reference monitoring well (Fig. 5.10), and directly beside the I/T-system Introduction (Fig. 5.10) that was installed in 2013. This location is known to be under threat, but not as seriously threatened or damaged as the area at the back of the Bredsgården tenement.

Figure 7.3 The drilling rig equipped with a hammer drill, used for creating the 1-inch-diameter holes to place the bundles of probes in.  
Photo: M. Vorenhout, MVH Consult.



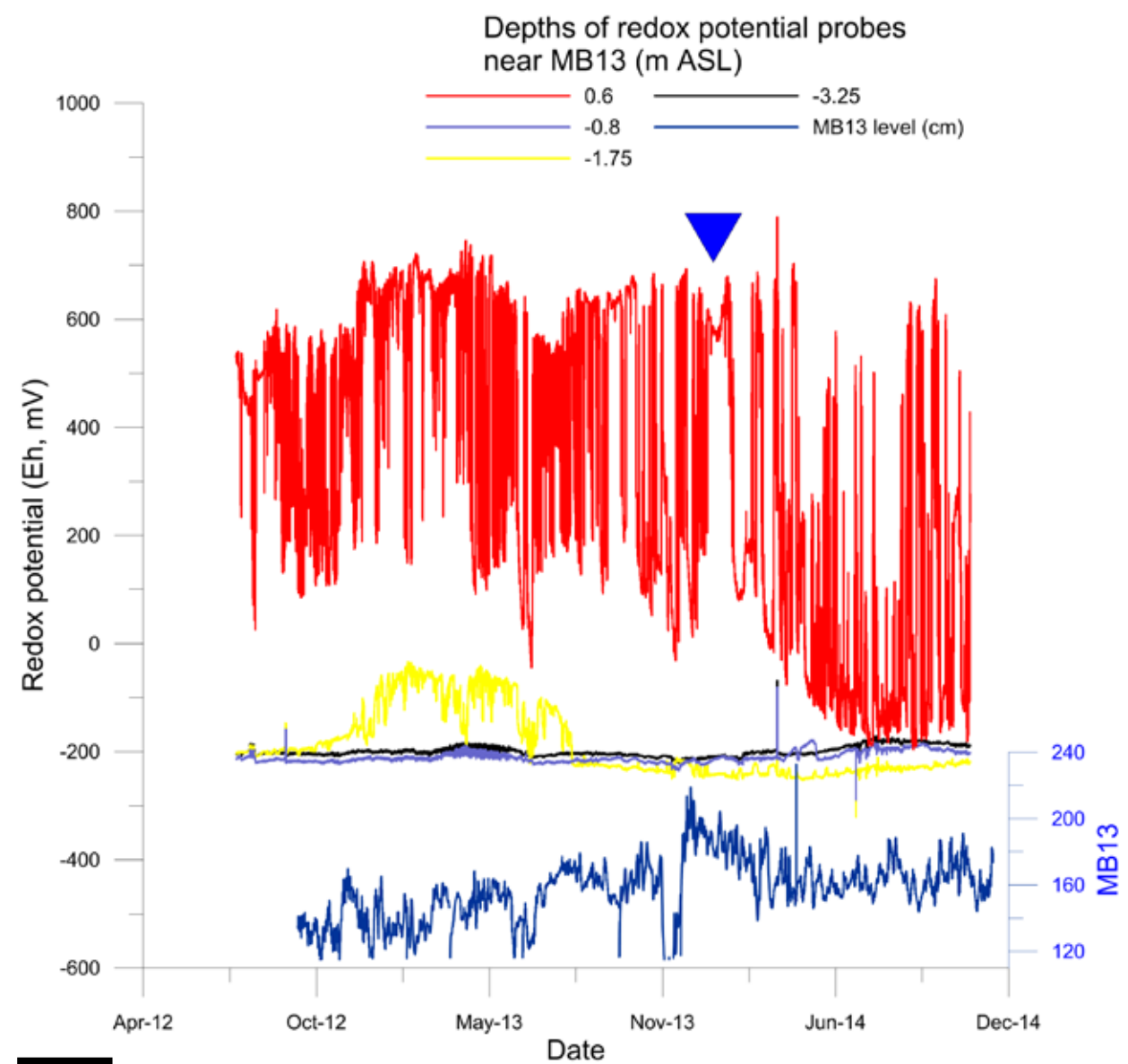


Figure 7.4

Fig 7.4 shows the results from a selection of measured depths. The redox situation in this location is that of a highly layered soil. The deepest levels measured, those below -1 metre asl, have been very stable and anoxic: conditions there are not influenced by water fluctuations. The layers nearer the surface are subject to water-table variations and consequently to variations in the redox conditions.

The changes that were found in 2014 show a somewhat more stable redox potential. Data from -1.75m asl show a lower and not rising redox potential (Fig 7.4). The redox potential higher up in the soil-profile (Fig 7.4, 0.6m asl) shows lower values as the baseline, even down to -200mV from the summer of 2014 onwards. The high variability is still there, but the overall levels are lower (red line in Fig 7.4). The water table at dipwell MB13 shows a rise from the winter of 2013/14 onwards, which may explain the drop in the redox potential later on.

Figure 7.4 A selection of measured redox potentials near monitoring well MB13. Note that the modern surface here is at 2.0 m asl.  
Illustration: M. Vorenhout, MVH Consult.

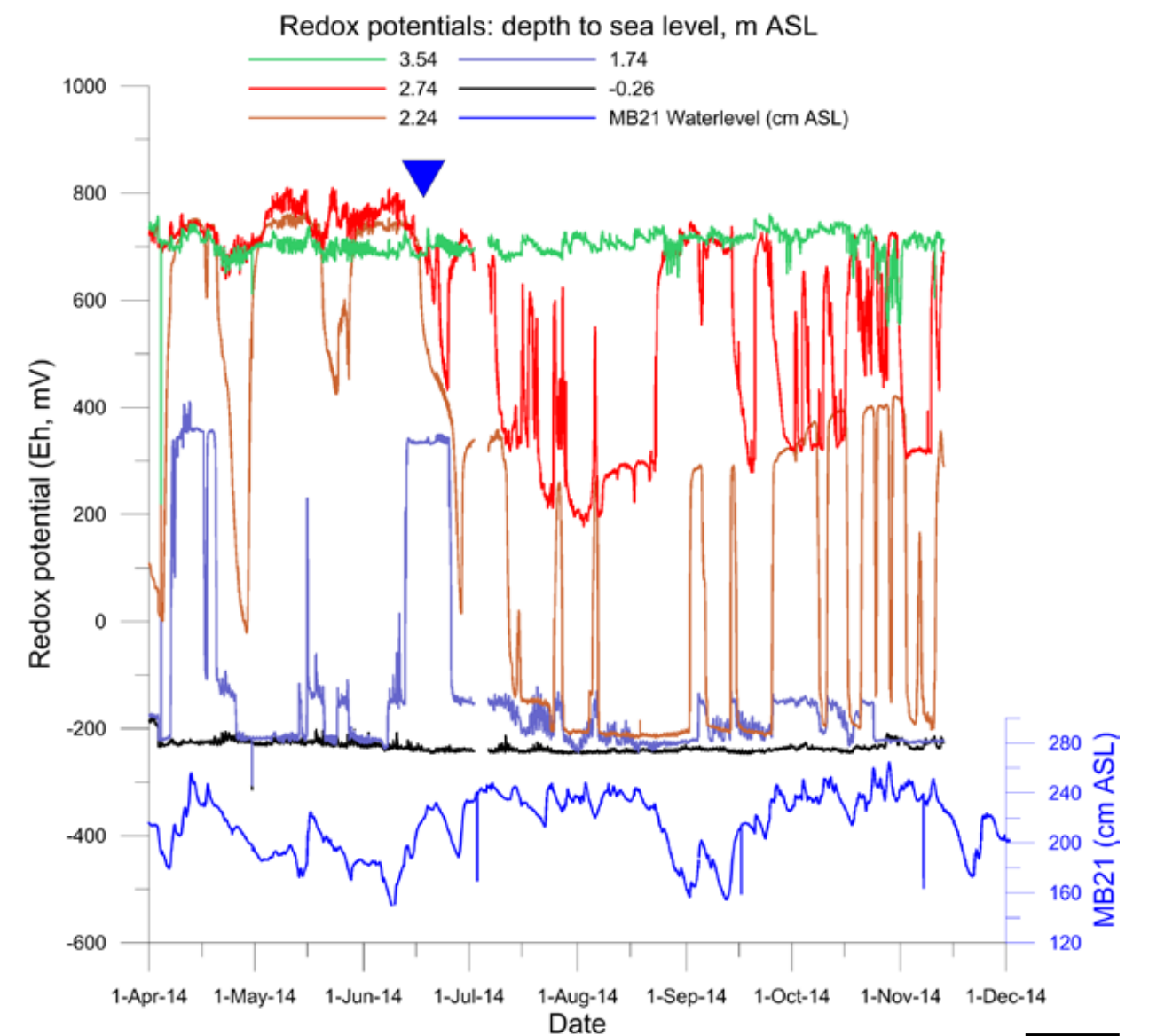


Figure 7.5

## MONITORING RESULTS NEAR SWALES IN BREDSGÅRDEN

The swales are situated several metres from the test-pit (see Chapter 6) at the back of the Bredsgården tenement. Redox probes were installed here to study the effect of the increased infiltration of water. Another set of probes was placed at similar depths as the oxygen probes in the test-pit, as installed by Matthiesen et al. in 2010.<sup>153</sup> For simplicity, only data from the latter set will be shown.

Figure 7.5 A selection of redox potentials measured in Bredsgården. The depths are related to the installed oxygen probes. Note that the modern surface here is at 4.14 m asl. The blue marker shows the start of long-lasting changes in redox values and variations.  
Illustration: M. Vorenhout, MVH Consult.

### Situation before mitigation

The redox potential at Bredsgården during 2014 is shown in Fig 7.5. A selection of probes is shown, namely those that are located at the same depths and next to the oxygen and moisture probes.

The first part of 2014 shows a redox pattern similar to that found in the previous years. The soil layers down to 2 m asl are highly oxidized. Redox potentials are well above 400mV, even reaching as high as 700mV. At some events, the redox potentials at 2.24 m asl drop to 0mV, but these events do not last very long. Soil layers between 2 and 0

m asl are reduced, and show events of oxidation. The oxic events at depths below 2 m asl (for instance 1.74 m asl in Fig 7.5) can be longer, and then the redox potential goes up to 350mV. This value shows fully oxic conditions. The deepest layers, at or below 0 m asl, are completely anoxic with more or less stable redox potentials of -200mV.

The oxidation events have some correlation with the groundwater levels measured in this location. Data from monitoring well 21 is shown in Fig 7.5, and a short drop in the water table in the first week of April 2014 coincides with the rise of the redox potential at 1.74 m asl. The redox potential at 2.24 m asl starts low, and goes up to 700mV as well. The consequent rise in the measured water table in MB21 in April 2014 does not directly affect the redox potentials. The expected drop starts some days later at 1.74 m asl, and some further days later at 2.24 m asl.

Changes found after mitigation

A change in standard redox potential values has been observed in the period after mid-June 2014 (blue mark in Fig 7.5). The second half of 2014 shows a redistribution of these stable levels. Now, only the soil levels higher than 2.74 m asl have a fully oxic and stable value. The measurement depths of 2.74 m asl and 2.24 m asl display redox potentials that start at other levels: 2.24 m now starts at -200mV, the same as the deeper layers; 2.74 m now starts at 200mV to 300mV, an oxic but not hyperoxic value.

More interestingly, 1.74 m asl does not show oxidation events any more after mid-June 2014. There is some variation, but all around -200mV, the same value as the deeper layers. 2.24 m asl now shows variations from as low as -200mV, going up at some events to +400mV [oxic conditions].

These shifts in redox behaviours can be caused by the longer periods of high water table, as shown by the measured groundwater levels in monitoring well 21 (bottom line in Fig 7.5). However, some other measures aimed at reducing the speed of water-flow were implemented in 2014 as well. This increased the amount of water that was recirculated from the area behind the hotel to the stepwise I/T-system (Chapter 8, Fig. 12). These

Figure 7.6 A selection of temperatures as measured near monitoring well MB13. Note that the modern surface here is at 2.0 m asl. Illustration: M. Vorenhout, MVH Consult.

measures increased the contact time of the water with anoxic conditions, which can result in lowered redox potentials in the water itself.

Future monitoring

Monitoring of the redox conditions at Bryggen should continue for several more years. It is unknown how long the actual stabilization of processes takes, but it can be assumed that it involves a number of years. The oxic periods near the swales are still present, and they last for several days. It is important to try to maintain stable conditions and thereby reduce the fluctuations in redox potential.

The probes nearest to the swales were damaged in the spring of 2014. This makes it impossible to monitor the direct effect of the swales. One of the questions that remains there concerns the redox potential of the water used for infiltration and how far a potentially higher redox potential is able to ‘travel’ into the archaeological deposits. Addressing this question will require a re-installation of probes, with some new ones in the swales.

SOIL TEMPERATURES

The presence of higher temperatures in the Bryggen deposits was previously shown by measurements in the monitoring wells. It is known that the rate of decay is speeded up by higher temperatures in the soils.<sup>154</sup> There can be several causes for higher temperatures to occur in the subsurface. The most obvious sources of additional heat are the buildings standing on top of the deposits, and the hotel’s below-ground parking area. Temperatures were measured at the same time as redox potential to identify the possible sources, and to improve our knowledge on the occurrence of and variation in higher temperatures.

The temperature sensors were located in the redox potential probes. Temperatures were also measured with the Hypnos III data loggers, together with the redox potentials. Temperature measurements are also performed in the monitoring wells when automated pressure transducers were installed, and in the test-pit. Only the data measured by the Hypnos systems will be focused on here.

Figure 7.7 A selection of temperatures as measured at the back of the Bredsgården tenement. Note that the modern surface here is at 4.14 m asl. Illustration: M. Vorenhout, MVH Consult.

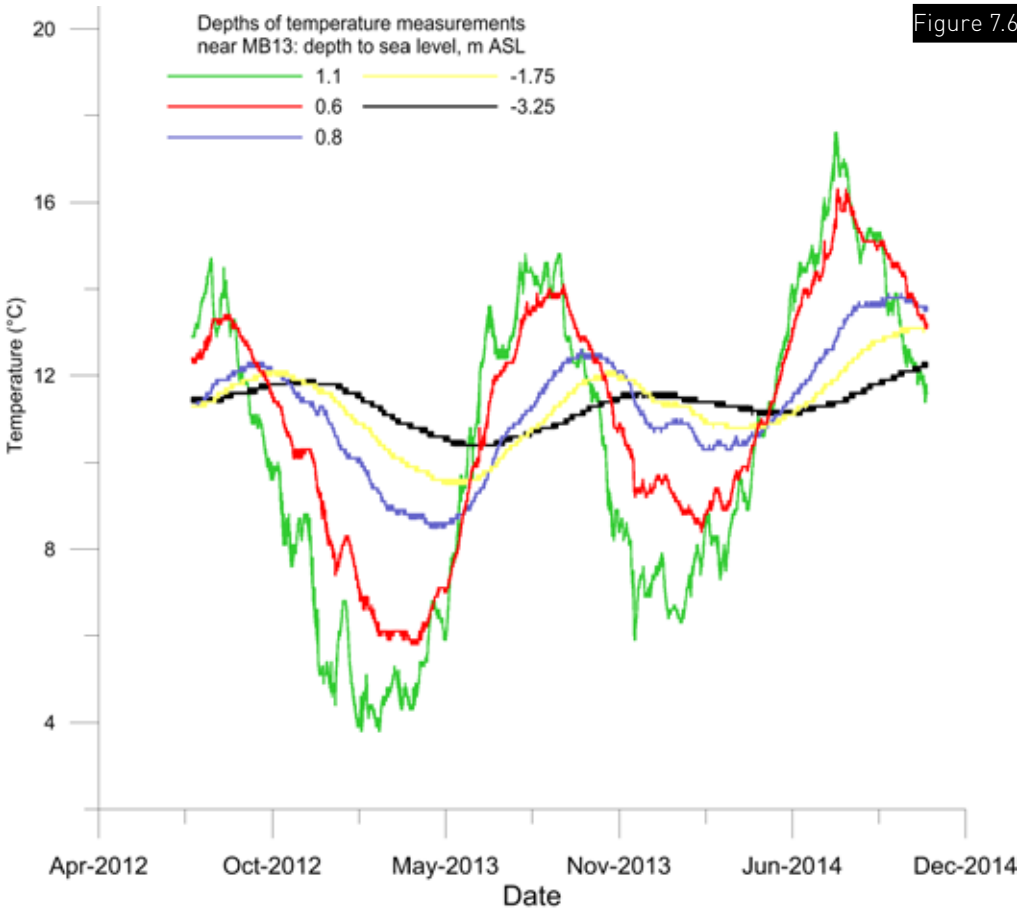


Figure 7.6

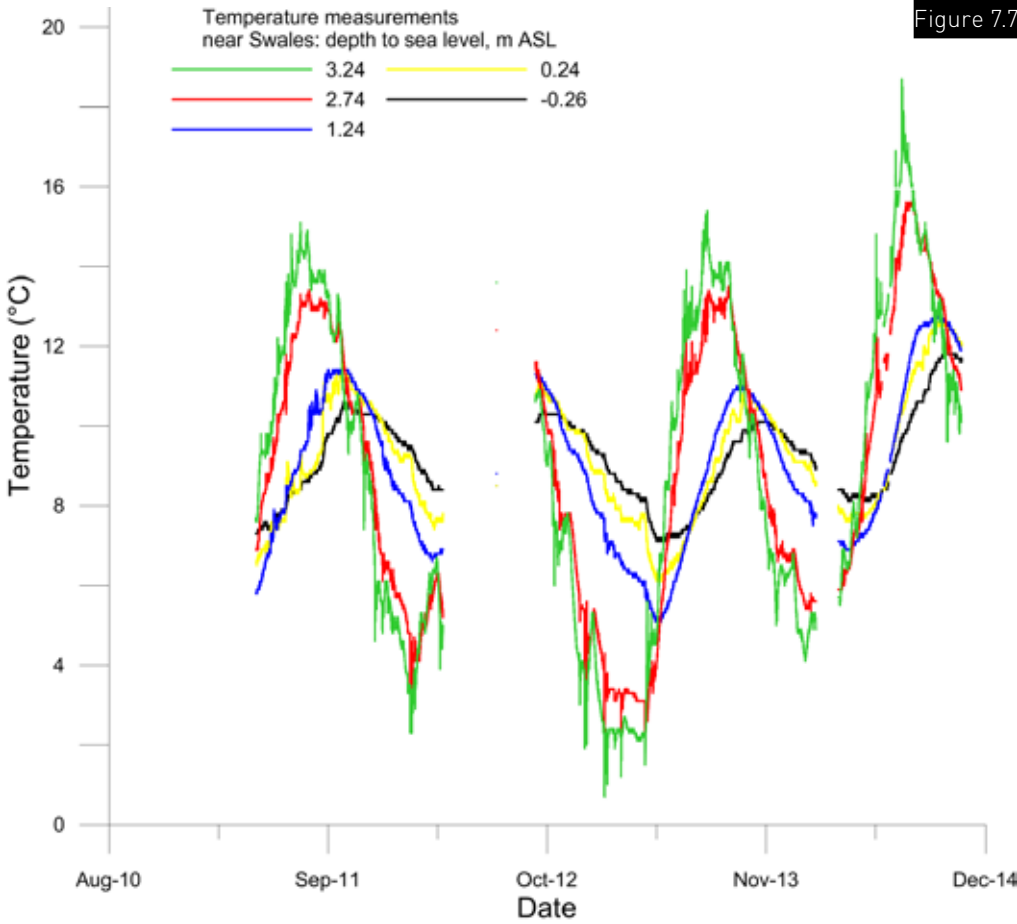


Figure 7.7



### Monitoring results for temperature

The temperatures measured near Monitoring well MB13, just outside the sheet piling, were several degrees Celsius higher than at Bredsgården. Fig 7.6 and 7.7 show a selection of temperatures at the two locations. Raised temperatures can especially be noted at the deeper measurement depths. Temperatures at 4.4 m below the surface (about 0 m asl) at the measurement locality near the swales fluctuate around 9.5°C, while those at the deeper depths (-3.25 m asl) close to the sheet piling fluctuate around 11°C.

The higher temperatures exist all year round. Interestingly, the variation of temperature within the year depends on the depth in the soil profile. Part of this is as expected, as air temperature influences the soil temperature, as exemplified by the temperatures at 0.9 m below the surface (1.1 m asl). There the soil is rather dry and therefore liable to be highly influenced by the air temperature. Seasonal variation can be detected down to the deepest measured depth of 5.25 m below the surface (-3.25 m asl), but is limited to a range of less than 1°C.

The mitigation work has not influenced the absolute temperature values directly. Having said that, the various measures were not designed to address the aspect of temperature, but on the reduction of oxic periods in the soil instead. In order to reduce temperatures, measures like thermal insulation of the buildings and parking area should be considered. The measurements show an increase in temperatures in 2014, compared to previous years. This is in part caused by generally higher air temperatures in Bergen, as 2014 was a relatively warm year: July was 4.7°C warmer than average.<sup>155</sup> However, the increase might also be an adverse effect resulting from the more stagnant water conditions. Stagnant water has more time to warm up near the parking area than flowing water. The increase is present at all depths, and should be studied further.

The monitoring of temperature will continue as long as the redox potentials are monitored and/or groundwater-level monitoring continues with automated loggers. Temperature monitoring will provide a valuable source of data once there are some measures available to reduce heat transfer into the Bryggen soils. The time series presented here will then serve as the baseline study prior to the implementation of such mitigation measures.

### CONCLUSIONS AND RECOMMENDATIONS

Bryggen is a unique archaeological site. Not at least for the amount of urban archaeology present (and described), but also for the intensity of monitoring. The value of monitoring a larger set of parameters is that one can combine data and gain knowledge. Measuring redox potential began well before the mitigation measures were implemented. The results complement those of the oxygen measurements. Where oxygen provides a high level of detail in the oxic region of the redox potential scale, the redox measurements with the Hypnos system give more information on longer-term effects and variations over the whole range of the oxic and anoxic environments.

The measurements of redox potential and temperature show that the mitigation measures already have an effect after a relatively short period. The redox potential data also show that it will take time before the entire soil/ water system becomes stable again. The dependency on stable water conditions is very high, and first results from the summer of 2014 show that conditions are improving. It is, however, expected that some more years will be needed before the oxidation/reduction situation will achieve a more stable condition.

Soil temperatures are still being raised by the buildings, and remain a matter of concern. All cities have artificially high temperatures relative to the countryside, and the effect of this - and its mitigation - needs to be given more attention in research and planning.

The installation of the redox probes and Hypnos system was the first of its kind in Norway, or even in any archaeological deposit sequence containing so many stone and timber obstructions. The three types of installation that were tried showed that all three are not perfect. Pushing the probes into the soil, using the 8mm probes, did not seem feasible. Installing a bundle of probes in a narrow hole was possible, but in some holes the soil did not collapse around the probes, meaning that the measurements in the unsaturated zone are not reliable enough. Attaching the probes to a dipwell tube made installation of the dipwell very difficult. Future projects that want to use an installation method without excavation are advised to use 12 or 16mm probes, with large-diameter extensions that will prevent the ingress of air from the top of the hole.

Redox potential can provide specific information about sub-oxic and anoxic conditions. The measurements at Bryggen show that interpretation can yield valuable insights, and can be used to follow environmental conditions that impact the preservation of organic deposits and archaeological remains. Interpretation should not only focus on absolute values, but include the general patterns that are observed in the time series.

The Bryggen project shows clearly that a long time series is needed before any monitoring regime can be considered truly useful. The measurements taken before mitigation work began provide the baseline for identifying changes due to the mitigation measures. The project aims to extend the present intensity of monitoring for a few more years, and the updated monitoring plan, due in 2015, will include several defined thresholds for redox potential values. The thing that makes it difficult to determine how long the actual monitoring period at Bryggen should be is the lack of a reference site where a set of probes has been installed in deposits of a similar nature, but not affected by mitigation measures. This site would provide comparative data, and would thereby represent a yardstick for assessing whether or not preservation conditions at Bryggen have attained the desired state.



08

## GROUNDWATER BALANCE

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Geological Survey of Norway



## URBAN GEOLOGY AND HYDROGEOLOGY

The landscape of Bergen is dominated by high mountains surrounding the city (Fig. 8.1). The city centre itself is relatively small with the newer areas clinging to the hillside. The centre is situated in a flat valley bottom a few metres above sea level, with hills running in a NNW-SSE direction on both sides. Due to the steep topography, the bedrock of the hillsides is either exposed or covered by a thin overburden of glacial sediments only (Fig. 8.2). However, at the bottom of the valley, underneath the actual city, the overburden can reach several tens of metres.

The subsurface at the Bryggen WHS has been subject to detailed ground investigations, and can be regarded as a representative stratigraphic sequence for the whole medieval centre of Bergen. The bedrock is covered by a sequence of superficial deposits (Fig. 8.3). The deepest natural deposit is glacial till. During and after the last glacial maximum about 9 000 years ago, the area now occupied by Bergen was covered by the ocean. Accordingly, the till is covered by substantial clay and beach deposits from the former sea bottom. The uppermost layer is comprised of various modern fills. The layer that makes the subsurface of the medieval centre of Bergen (the districts of Bryggen and Vågsbunnen) special are the archaeological deposits sandwiched between the beach deposits and the modern material. This layer reaches thicknesses in excess of 10 metres in places, is highly organic, and is protected by the Cultural Heritage Act.

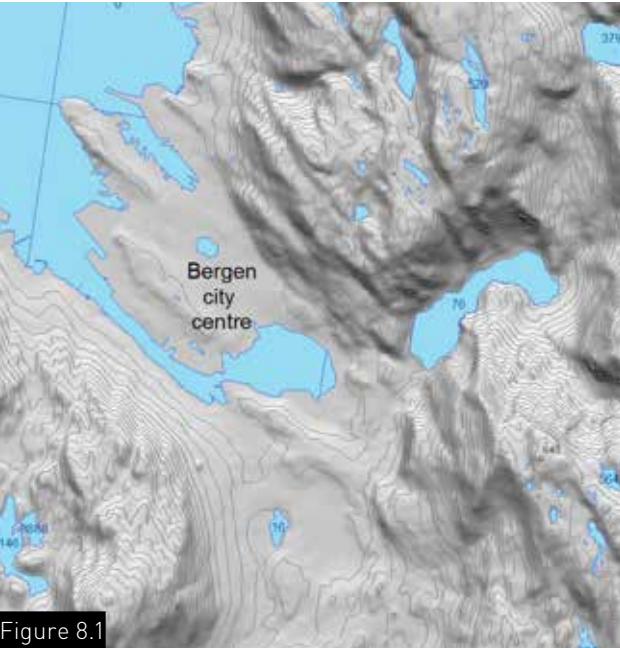


Figure 8.1

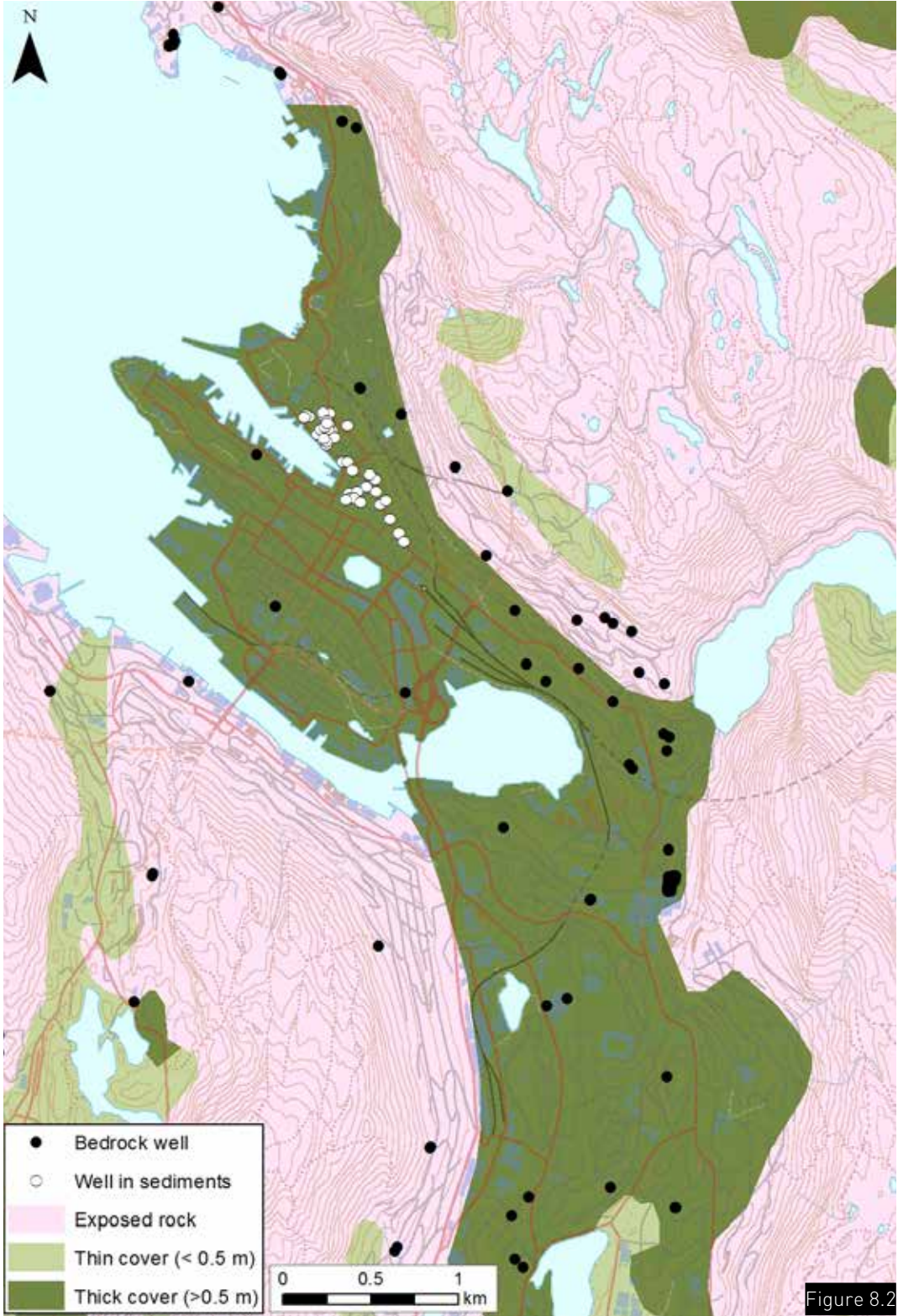


Figure 8.2

Figure 8.1 Physical geography of the Bergen area.  
Map: A. Seither, NGU.

Figure 8.2 Depth to bedrock and position of observation wells. Map: A. Seither, NGU.



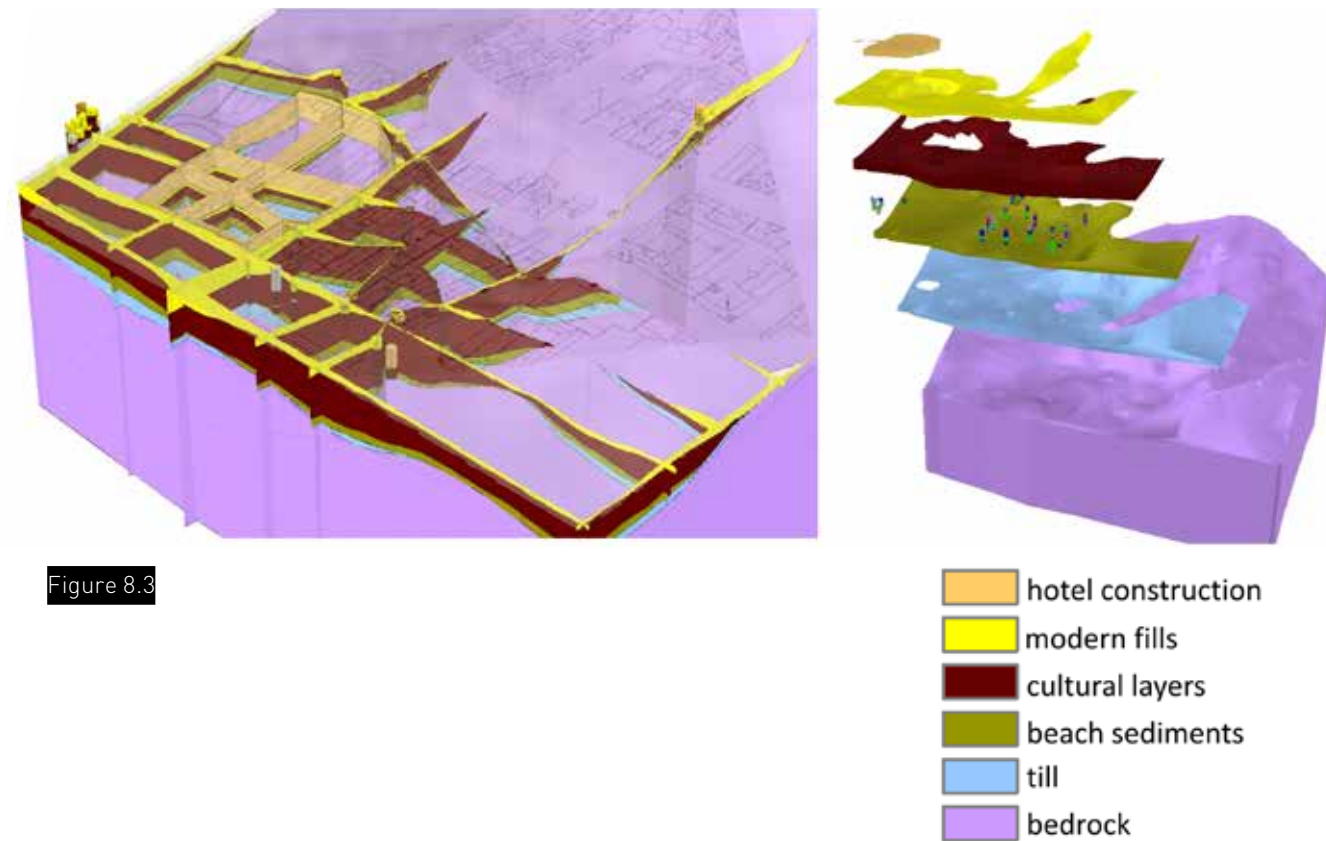


Figure 8.3

The hydrogeological situation of the medieval city centre is defined by the wet climate as well as its location between a steep hillside and the harbour. The regional groundwater flow is mostly controlled by the local topography and the groundwater level can be pictured as a softened, simplified representation of the terrain surface.

There are few measurements of groundwater pressure head in the recharge area stretching along the hillsides north of Bryggen. Presumably, groundwater roughly follows the NE to SW trend of surface water, but flowing mostly through a system of open fractures and weak, permeable bedrock zones of greenstone, phyllite and gneiss, before feeding the superficial deposits under Bryggen and Vågsbunnen. Local precipitation partly infiltrates into the subsurface and contributes to the groundwater underneath the old settlement.

The groundwater generally flows from the recharge area in the NE towards Bryggen and out into the harbour (Fig. 8.4). This is reflected in the groundwater measurements in the superficial deposits of Bryggen. However, the local groundwater conditions are influenced by a complex interaction of various factors:

- Precipitation (~2250 mm/year) and evaporation (~450 mm/year)
- Properties of the deposits: sand, clay, refills, bedrock, fracture zones, etc. and their hydraulic properties
- Tidal variations (up to 2 m) and saltwater intrusion
- Extraction or infiltration: wells, drainage systems, stormwater infiltration; leaks through the sewer, storm- and wastewater pipes
- Surface conditions: buildings, asphalt, cobblestones, green spaces, etc.
- Pipe and cable trenches
- Underground installations: sheet piling around the SAS hotel, basements, tunnels

Figure 8.3 3D visualization (GSI3D) of the deposit sequence underneath Bryggen's timber buildings, extrapolated between neighbouring monitoring well-borehole columns. An exploded view of the 3D sub-surface model is shown above. J. De Beer et al., 2012.

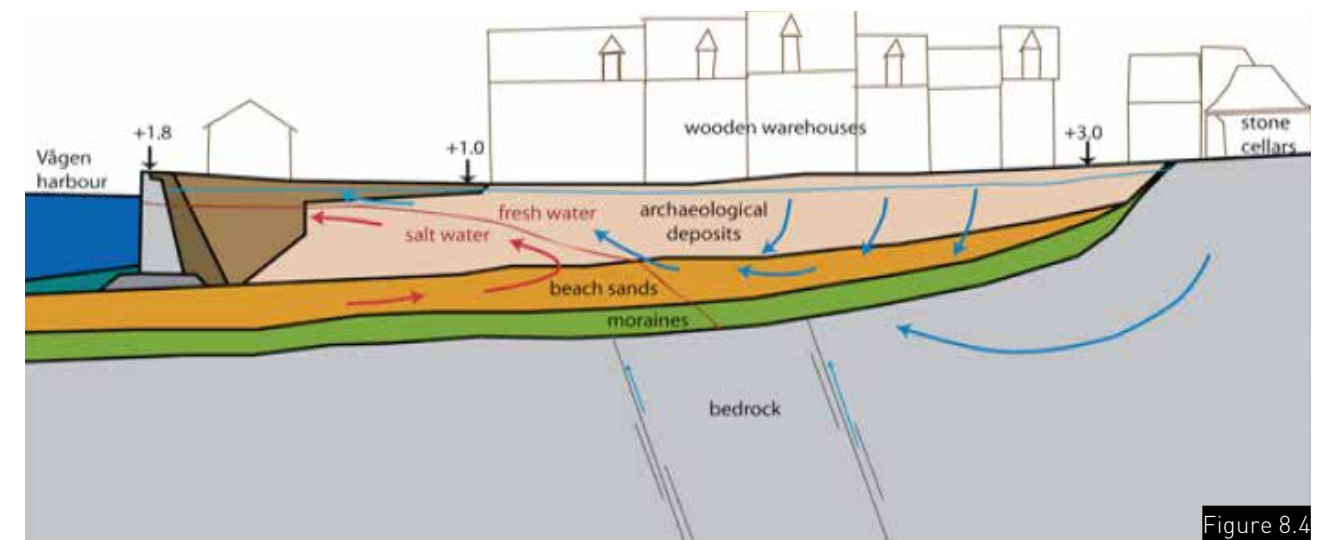


Figure 8.4

## GROUNDWATER LEVELS

### Objectives and monitoring

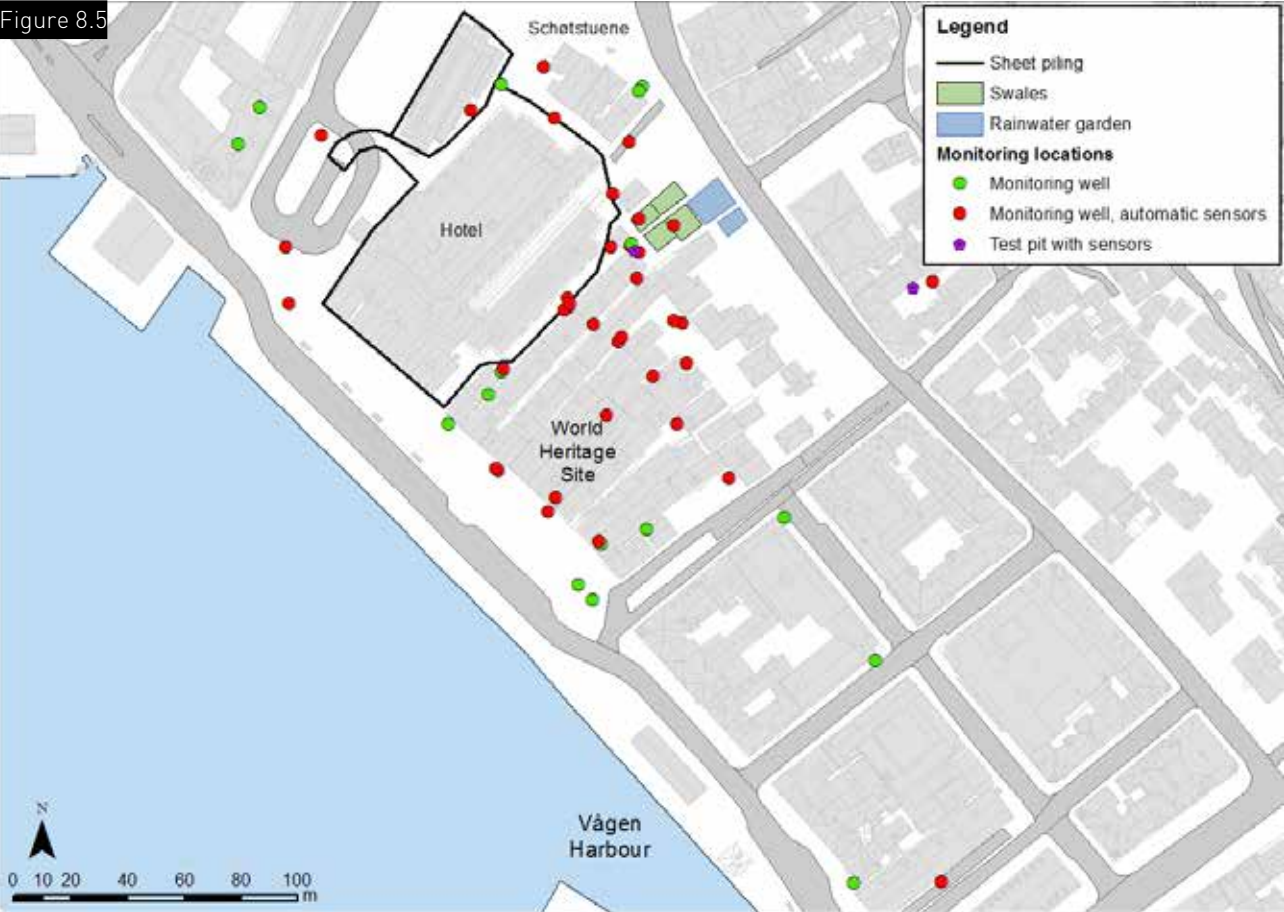
In order to evaluate the connection between groundwater, the decay of organic archaeological deposits, as well as subsidence issues, a monitoring system was established in 2001. Initially, this network of monitoring wells was placed to understand the complex flow system in the area and to identify the causes of the documented locally-lowered groundwater levels and increased subsidence rates.

A proper understanding of the groundwater flow system and causal relationships between drawdown and subsidence rates was achieved during the period 2005-2008. In this period, automated groundwater-monitoring equipment with a high frequency of measurements was installed and a hydrogeological flow model was constructed.<sup>156</sup> During the past decade, the monitoring network has been extended in order to be able to design mitigation measures and to follow their effects. The main goal was to find appropriate measures that would reduce the loss of archaeological deposits and mitigate the subsidence of the ground surface and historic buildings.

The key challenge for the management of the area is related to shortage of groundwater in the organic, archaeological deposits. A low and instable water table causes increased access of oxygen to the organic materials, leading to their decay and the concomitant subsidence of buildings above. All measures were thus primarily directed towards raising and stabilizing groundwater levels. The long-term goal for the area is to elevate groundwater levels to generally about 1 m below the surface.<sup>157</sup>

Figure 8.4 Cross-section from the harbour to the rear of Bryggen, giving a simplified picture of the sub-surface sequence of principal deposit types and the local water flows (modified and extended by J. de Beer after E. Mørk, Stiftelsen Bryggen).





The monitoring network was installed in order to:

- verify that the measures to raise and stabilize groundwater levels are effective;
- keep track of possible negative effects on buildings and archaeological heritage while the measures are being implemented;
- document that the preservation conditions in the area improve due to the initiatives.

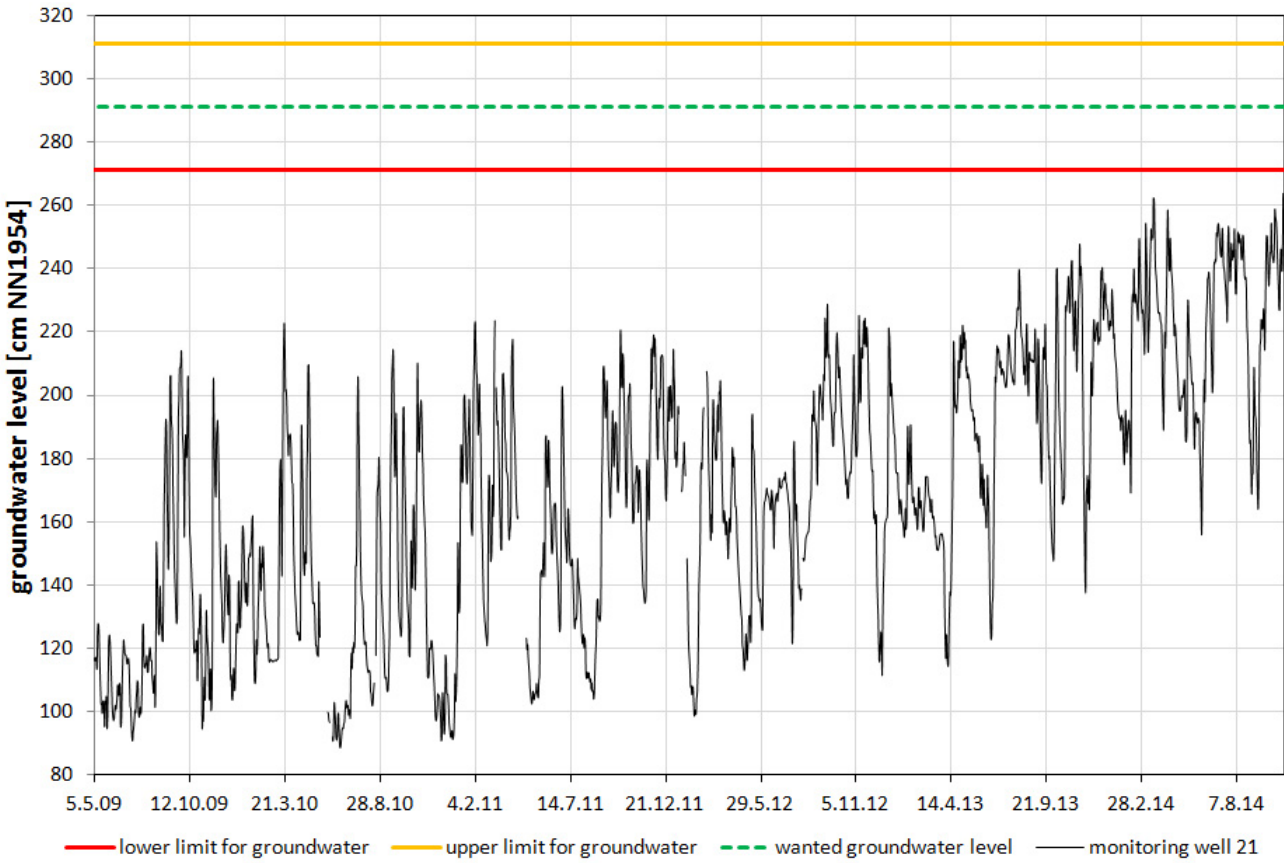
Over a period of 14 years, 47 groundwater monitoring wells have been installed in the area. In addition to these monitoring wells, a rainwater gauge has been installed on the roof of Bryggens Museum, adjacent to the Bryggen site. The rainwater gauge also includes an air pressure sensor that is used to calibrate the measured groundwater pressures for temporary changes in barometric pressure. An overview over the locations of these wells is given in Fig. 8.5. 33 of these wells have been equipped with

automated sensors that measure groundwater pressure and temperature. In addition, there is a sensor in the Vågen harbour, to measure tidal variations.

### Situation before mitigation

Continuous logging of the groundwater level in several monitoring wells in the area showed that the groundwater levels within the archaeological deposits at the world heritage site are only indirectly influenced by precipitation. However, the average groundwater level variations in 'undisturbed areas' within the archaeological deposits are highly correlated with the average tidal fluctuations in the Vågen harbour. Accordingly, the groundwater pressure within the archaeological deposits is controlled by the groundwater pressures in surrounding ground materials that have a good hydraulic connection to the harbour. As an example, the monitoring wells MB17 and MB23, whose intake filters are in beach sands below the archaeological deposits (around 12 m below the surface), show a quick response - only about two hour delay - to tidal variations in the harbour.

Figure 8.5 Overview map of groundwater monitoring wells (dipwells).  
Map: A. Seither, NGU.



These pressure variations are then propagated to the archaeological deposits above. A similar situation occurs below the quay at the front of Bryggen, where the ground consists of a mixture of post-medieval and medieval deposits, along with highly permeable, mostly inorganic fills for the early 20th century quay extensions and in the ditches containing service infrastructure (sewage pipes, water mains, etc.). Tidal variations are propagated effectively through the more highly permeable materials at the quay front and further into the archaeological deposits below the historic buildings. The rapid, short-term fluctuations are damped, but long-term average tidal variations are clearly observed within the deposits in a more dominant way than meteorological variations.

These observations made it clear that it is not sufficient to monitor groundwater pressure within the archaeological deposits alone, even though they are of course the main materials of interest. The archaeological deposits are

part of a complex underground composition that is hydraulically interconnected. In order to understand the processes and to find solutions, it is absolutely necessary to investigate neighbouring ground conditions and groundwater pressures as well.

The groundwater pressures in wells MB17 and MB23, below the archaeological deposits, are always lower than in the overlying archaeological deposits (which are up to eight metres thick). This is a very important observation, because groundwater always flows from points of higher pressure to points of lower pressure. It means that the direction of groundwater flow is downward, draining the archaeological deposits. Increase of the deeper pore pressure will reduce downward flow through the archaeological deposits and can locally even change the flow direction from downwards to upwards. It is essential to understand this relationship when designing measures to reduce drainage of the archaeological deposits.

Figure 8.6 Groundwater level in monitoring well MB21.  
Drawing: J de Beer, NGU.

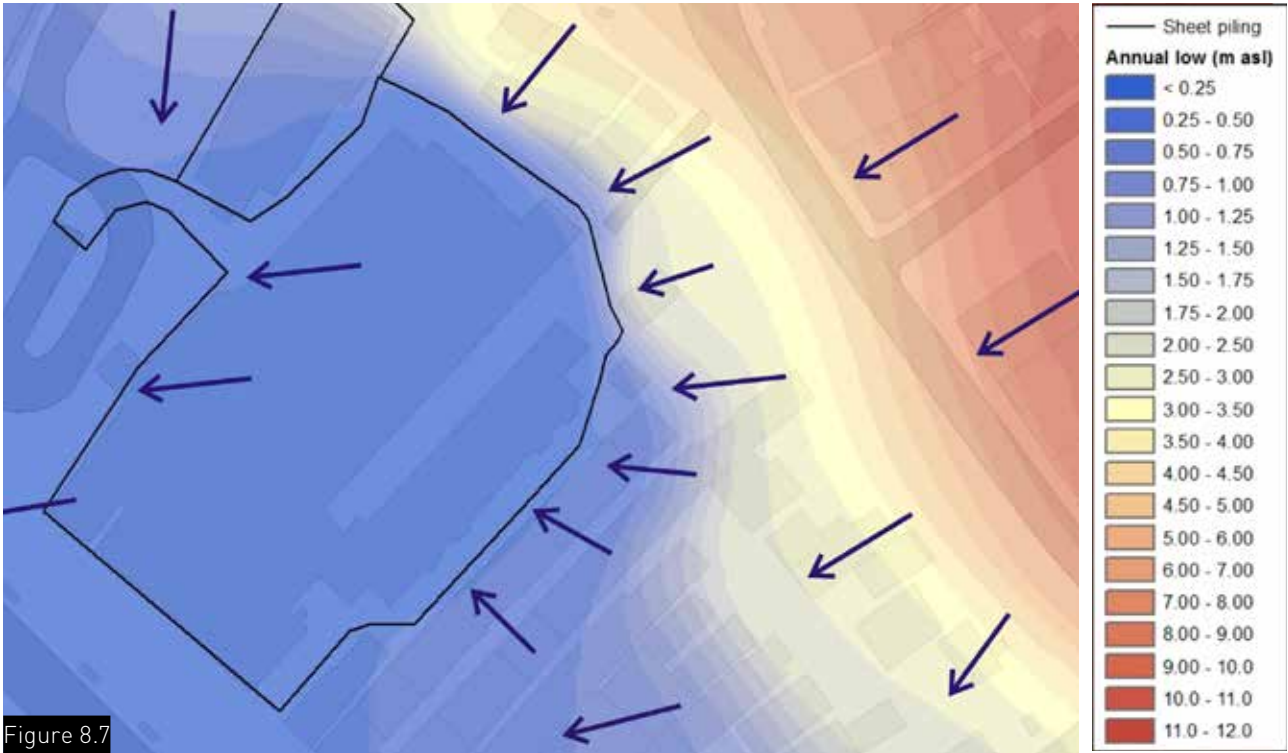


Figure 8.7

## Methods

### Measures concerning the hotel area

Since increased subsidence and low groundwater levels began to be observed in 2001,<sup>158</sup> the neighbouring hotel area was suspected of playing a role. The increased monitoring efforts since 2005, combined with groundwater-flow modelling, strengthened this suspicion (Fig. 8.7).

A practical but temporary test in November 2010 unmistakably showed the causal relationship that the groundwater pressure underneath the archaeological deposits was directly dependent on the drainage level around the hotel's underground parking and service area,<sup>159</sup> indicating considerable leakages in the surrounding sheet pile wall. Hence, the primary task became to reduce the flow of groundwater from the world heritage site towards the hotel area.

To understand the cause of the groundwater lowering and design effective mitigation measures, it is essential

Figure 8.7 Simulated groundwater level and direction of flow at Bryggen. The dashed line indicates the hotel area. J de Beer, 2008.

to understand the hotel construction in detail. These details are reported in separate scientific reports.<sup>160</sup> A simplified explanation is given here. The (watertight) parking area below the hotel is built on a base layer of highly permeable gravel and surrounded by a sheet pile wall that was rammed down to either bedrock or at least to a layer of low permeability below the archaeological deposits. The groundwater level in the gravel layer is governed by an overflow pipe through the western sheet pile wall, keeping the groundwater level at average sea level. The surrounding sheet pile wall's top rim is on average located about 1.0 to 1.5 m below the ground surface. Groundwater-level observations clearly indicated that the sheet piling was not watertight, and showed both shallow and deep leakages.

The obvious first measure was to raise the overflow level of the drainage system below the parking area. This would raise the groundwater pressure below the parking area, thereby reducing the groundwater flow from the surrounding archaeological deposits towards the hotel. The maximum drainage level that could theoretically be attained below the hotel is dependent on two factors: firstly, the specified maximum pressure below the parking area's floor (too much pressure would involve a risk of updrift); and secondly, the lowest elevation of the top of the sheet pile wall ('the rim of the bath-tub', where water would start spilling out).



Figure 8.8

Accordingly, the drainage inspection well at the western corner was supplied with a vertical pipe with a new overflow level at 0.45 m asl in November 2010. This led to an immediate increase of the drainage level and, as a result, the groundwater pressures in monitoring wells below the archaeological deposits as well as in wells close to the hotel rose.<sup>161</sup> However, the groundwater level (pressure) under the hotel did not rise to the newly installed drainage level of 0.45 m, indicating that other overflows had been activated elsewhere along the sheet piling in the southwestern part of the parking area. Inspection of the sheet piling confirmed this. Groundwater was leaking out through large cavities (or partly missing sheet piles) where sewage and other pipes crossed the wall, and the smaller holes cut to receive the upper ends of the many slanting ground anchors (anchor holes).

A considerable amount of work was devoted to sealing as many as possible of these anchor holes. At locations where parts of individual sheet piles had been damaged or deliberately removed, the wall was repaired by adding a concrete barrier on top of the sheet piles up

Figure 8.8 Photo showing deterioration of the sheet piling and a point with substantial leakage. Photo: J. Hausvik, Bergen Bydrift.

to the required elevation. It is important to realize that the anchor holes along the hotel's lower-lying front part (between average sea level and about 0.70 m asl) functioned as overflow points for groundwater below the parking area, while anchor holes at the higher-lying rear and middle part of the parking area functioned as drainage points, so that groundwater could flow quite freely from the archaeological deposits into the hotel area.

In January 2012, the drainage inspection well at the hotel's western corner was replaced with a new manhole with an overflow level of 0.7 m asl. A check valve was installed to prevent reflux of seawater into the drainage system below the parking area during higher tides. Seawater intrusion has been drastically reduced by this mitigation measure, although temporary inflow still occurs when the tidal level is higher than the sheet pile wall's rim and direct overflow occurs.

But even though the drainage level was raised and anchor holes were sealed, the water flow from the world heritage site into the hotel area could not be stopped entirely. Particularly the northeastern part of the sheet piling adjacent to the Schøtstuene complex continued to leak. The problem was approached by continuously pumping intruding water and routing it back into the shallow infiltration system on the outside of the sheet piling (see section Infiltration measures).





Figure 8.9



Figure 8.10

### Infiltration measures

Other actions were directed towards a more sustainable management of surface water, aiming to restore the natural water balance of the subsurface to a state as similar as possible to what existed prior to the hotel's construction. Several measures that focus on infiltration and water retention have been implemented.

In those areas where the ground was highly compacted, the topsoil was reworked and partly replaced by gravel with high infiltration capacity. At critical locations, the fine-grained layer supporting the cobblestone pavements was exchanged with more permeable material to facilitate rainwater infiltration. These measures have reduced stormwater runoff considerably and improved local infiltration of rainwater. So-called swales have been constructed at two locations behind Bryggen to capture surface runoff and facilitate infiltration (Fig 8.9).

A rainwater garden (Fig. 8.10) has been constructed between Øvregaten (the High Street) and Bryggen. Stormwater from the urban area upstream of Øvregaten is connected to the garden, enabling a large amount of water storage and gradual infiltration to the underlying archaeological deposits. The construction of the rainwater garden ensures the capture of pollutants present in stormwater; contaminated topsoil can be replaced at regular intervals. Details of the rainwater garden are described in chapter 10.

The rainwater garden, swales and permeable pavement together form a so-called 'treatment train'. A schematic illustration of the treatment train is given in Fig. 8.11.

Shallow infiltration pipes were installed at various locations to ensure direct subsurface infiltration of water for replenishment of the groundwater reservoir. Infiltration systems have been constructed in the area with the largest 'drop' in the groundwater level, just outside of the sheet piling around the hotel's parking area, as well as around Schøtstuene, where the ground

Figure 8.10 Rainwater garden under construction. Photo: J. de Beer, NGU.

Figure 8.9 Swale (left) and channel in the cobblestones (right). Photo: J. de Beer, NGU.

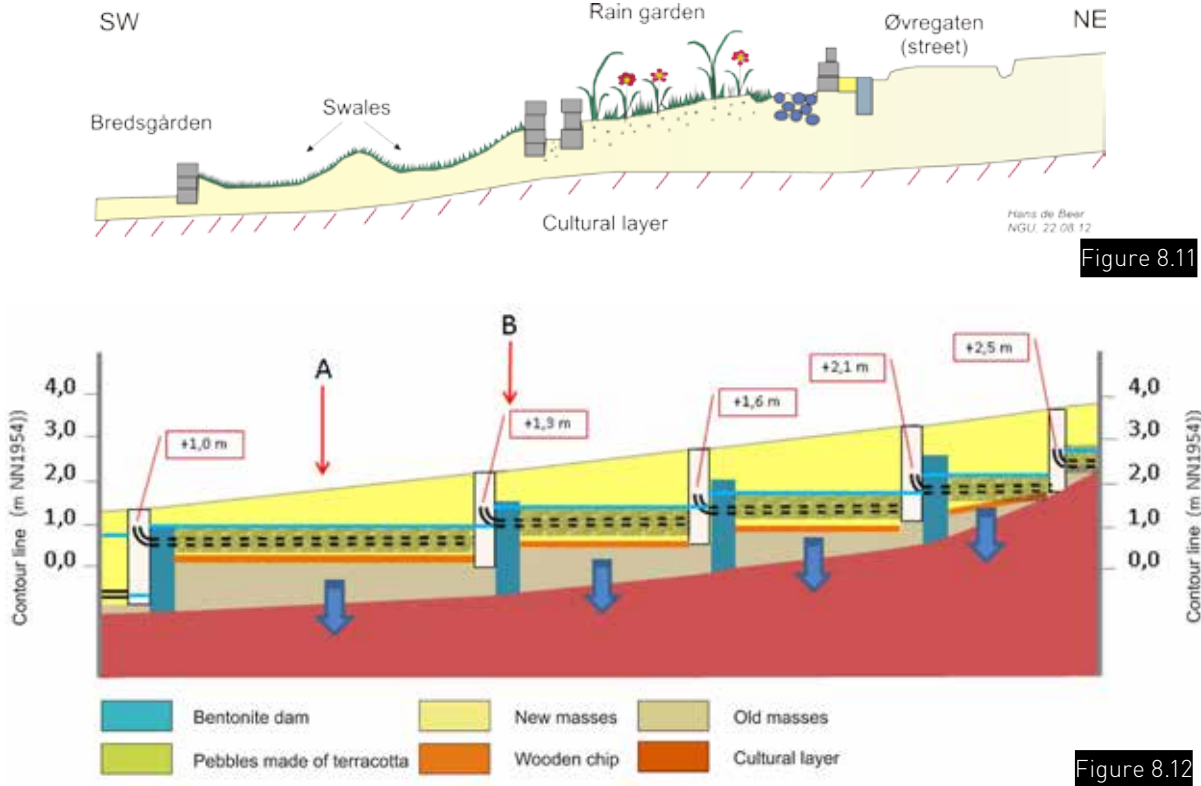


Figure 8.11

surface lies significantly higher. Arguably the most important of these measures is the stepwise infiltration-transport (I/T-) system in the Bugården tenement's passageway between the hotel and the historic buildings. The main motivation for the design was to reduce the groundwater flow along the sheet piling towards the harbour, and to be able to regulate groundwater levels in relation to the bottom levels of the foundations of the buildings in the northern Bredsgården tenement. The principle of this I/T-system is illustrated in Fig. 8.12.

The I/T-system is basically a series of buried infiltration pipes, a sequence of bentonite-clay dams, and drainage inspection wells with sand traps behind each dam. The infiltration pipes of each section have their outflow in the closest well downstream. Since the wells are open at the bottom, water discharge from the upstream section can infiltrate into the ground. The groundwater level of each section can be controlled individually by modifying the height of the outflow into the wells. The groundwater level of each section was arrived at based on the desired groundwater level and the level that is

Figure 8.11 Schematic illustration of the water 'treatment train' at the rear of Bryggen. Drawing: J. de Beer, NGU.

Figure 8.12 Schematic illustration of infiltration-transport (I/T-) system. Drawing: J. de Beer, NGU.

acceptable for the foundations of Bugården’s historic buildings. Water meters were installed in order to keep track of the discharge of water and to determine how much water infiltrates into the archaeological layers. Another important feature of the infiltration trench is that its bottom was intentionally covered with woodchips. These woodchips serve as a buffer layer between the atmosphere and the archaeological deposits. Intruding oxygen will react with the woodchips and thus be removed from the system before it can reach the vulnerable archaeological deposits beneath. Photos of the I/T-system during construction are shown in Fig. 8.13.

**Effects of mitigation on groundwater levels**

Continuous monitoring of the groundwater level before and during mitigation works have documented that the project was successful. The groundwater level could be raised to a level that keeps large volumes of vulnerable archaeological deposits saturated. Seasonal groundwater-level variations that caused worsened preservation conditions during the summer months have diminished.

Is it possible to document the effect of individual mitigation measures? Yes, it is - and the link between actions and effects becomes very clear when one looks at the measurements series of monitoring wells MB17 and MB21 (Fig. 8.14 and Fig. 8.15). Groundwater-level data are available on an hourly basis. This frequency has been essential in order to follow immediate and short-term effects of mitigation measures, but it gives too much detail to assess the general trend of groundwater-level



Figure 8.13 The I/T-system under construction.  
Photo: A. R. Dunlop, NIKU.



Figure 8.13

changes. The original data have been averaged out over longer periods of time. The grey line in the background of the figures shows the average daily variations of the groundwater level. Owing to short-term variations it is still difficult to see the general trend over time. By calculating a moving average over a period of three months, the ‘noise’ in daily averaged measurements was removed, showing long-term changes. As shown in Fig. 8.14 , the mean groundwater level was initially low. The first action, modification of the drainage system below the hotel’s parking area (see sectio Measures concerning the SAS hotel), increased the deep groundwater pressure almost instantly, reducing the gradient towards the existing drainage system. This in turn led to a sudden and very prominent upsurge of the groundwater level in monitoring well MB17, in the sandy deposits below the archaeological deposits. After various repairs and infiltration measures, the overall groundwater level could be kept at a high level. Significant drops in the groundwater level in recent years were caused by

pumping that was necessary for maintenance work, and are thus not representative for the overall groundwater-level situation.

The impact of active infiltration of water into the ground is best illustrated with the measurements series from well MB21 (Fig. 8.15). As with well MB17, the overall groundwater level rose after the first measure, but season variations still had a distinct influence on the groundwater level. Such seasonal lows pose a threat to the archaeological deposits, because the deposits dry out temporarily and come into contact with higher concentrations of oxygen. The construction of the I/T-system and the swales provided the deposits with an almost continuous supply of water. The system compensates for water shortages in drier periods and ensures water-saturated conditions at most times, independent of weather conditions.

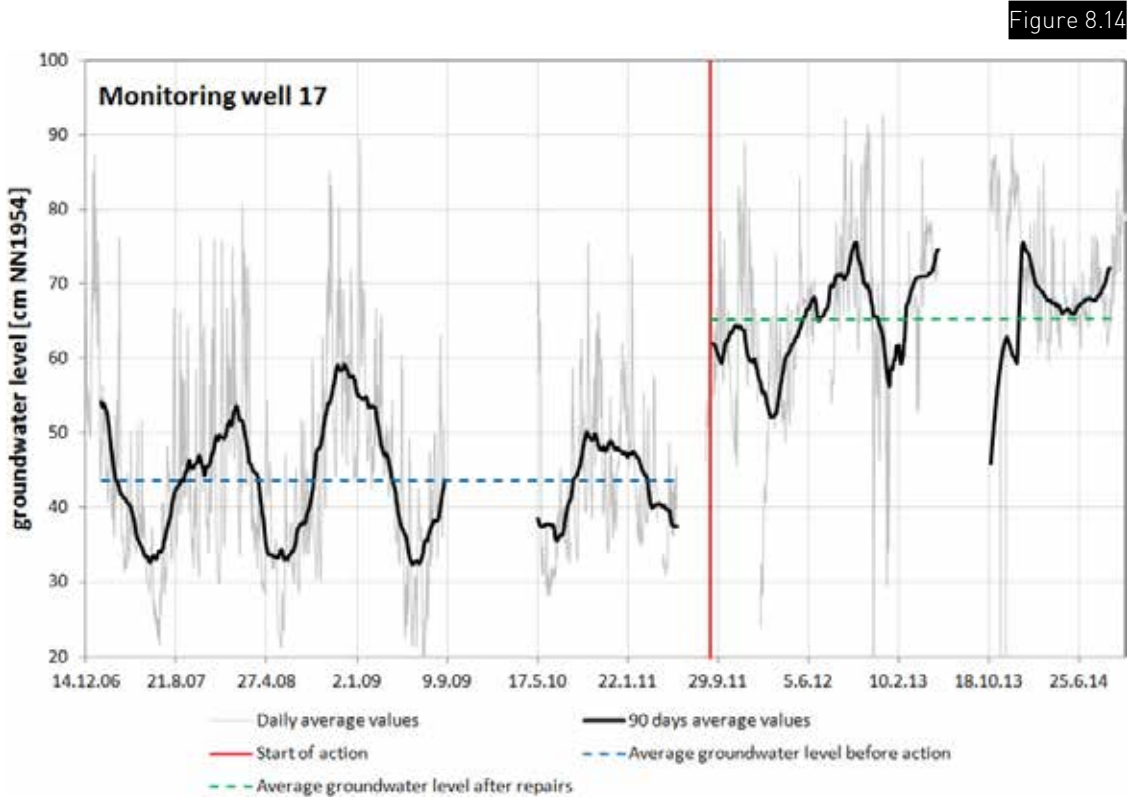


Figure 8.14 Groundwater level in monitoring well MB17. The grey line shows daily variations of the groundwater level. The black curve gives a simplified impression of the groundwater level, by showing average values over three-month intervals. Through a combination of several mitigation measures, it has been possible to raise the groundwater level (by on average c. 20 cm). Drawing: A. Seither, NGU.



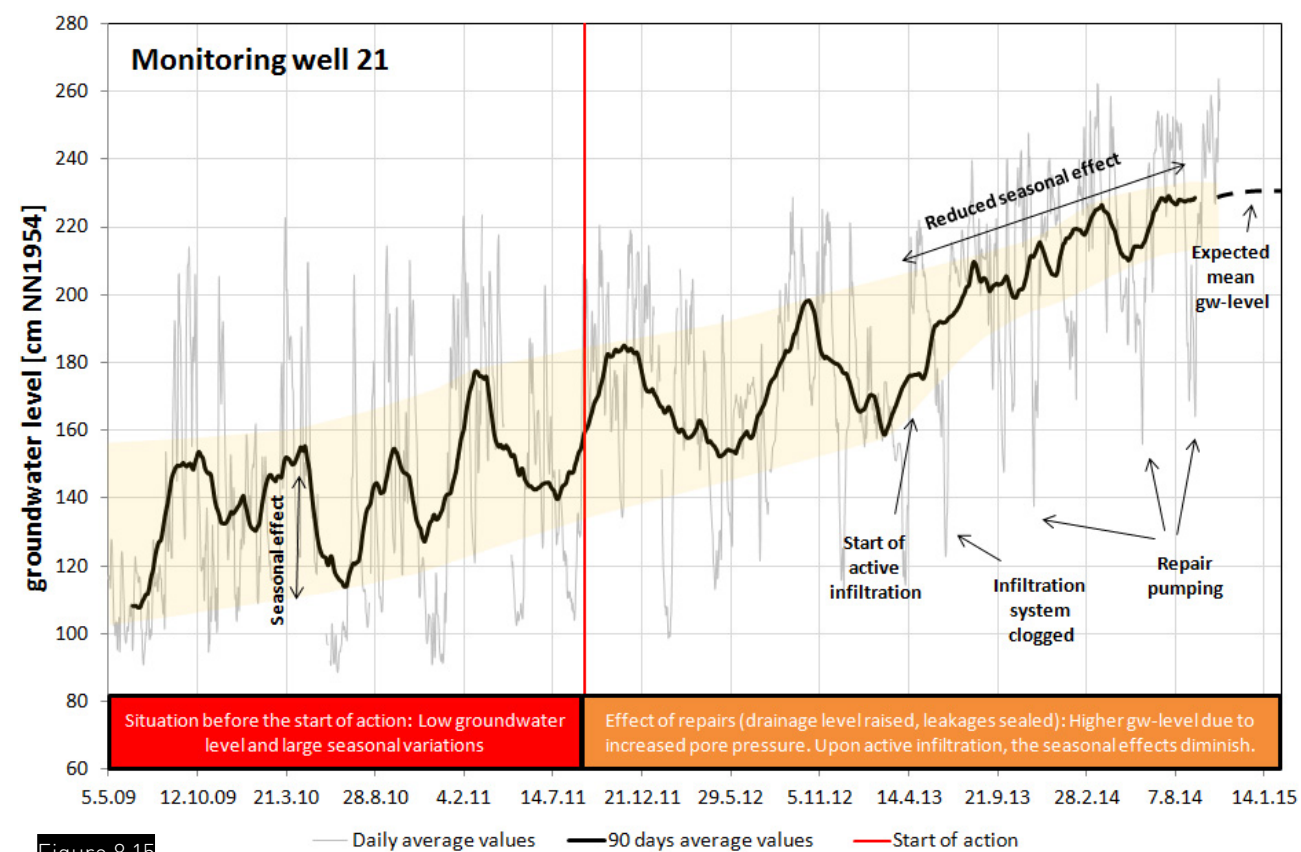


Figure 8.15

## Future groundwater level monitoring

Since 2011, various measures to raise the groundwater level have been implemented. The substantial success of these measures has been documented by continuous logging of groundwater levels in the area. However, even though the most active part of the project is now over, it is necessary to continue monitoring. It is expected that groundwater levels will stabilize at a higher level than before and that seasonal variations will flatten out, but it takes at least one hydrological year (starting September 1th) to be able to calculate a trend. Furthermore, continued monitoring will make maintenance of installations easier, since problems such as clogging of infiltration systems can be detected at an early stage.

## GROUNDWATER TEMPERATURES

Most discussions of problems and solutions at Bryggen focus on the groundwater level and the moisture content in the archaeological deposits. Thus it may not be intuitive to monitor groundwater temperature as well, but these data are a useful supplement to other measurement series. Temperature data are necessary for, amongst others, a proper calibration of oxygen measurements, and they can be used to investigate heat flow and temperature effects on decay in archaeological deposits. Groundwater temperature is measured with the same automated manometers that are used for groundwater-level monitoring.

The aim was to reduce the temperature of the groundwater to a mean of no higher than 9 °C, and it was expected that this could be achieved as a by-product of measures that deal with groundwater and surface water.

Figure 8.15 Groundwater level in monitoring well MB21. The grey line shows daily variations of the groundwater level. The black curve gives a simplified impression of the groundwater level, by showing average values over three-month intervals. Drawing: A. Seither, NGU.



Figure 8.16

## Monitoring results

### Situation before mitigation

The temperature of groundwater in non-urban areas is generally similar to the mean air temperature. Urban groundwater, however, is typically warmer, because the adjacent ground is influenced by heated buildings and compact surfaces.

The mean annual air temperature in Bergen is 7.6 °C, and all monitoring wells show a higher mean groundwater temperature (8.4 °C - 13.6 °C). Heat sources that can cause higher temperatures are heated buildings and underground infrastructure. Ground heating will also occur below dark surfaces, such as asphalt. Fig. 8.16 shows the average groundwater temperatures in the monitoring wells. The highest groundwater temperatures at Bryggen are measured in monitoring wells near the hotel's parking area, with a gradient towards more 'natural' groundwater temperatures upstream of Bryggen.

Figure 8.16 Average groundwater temperatures in monitoring wells at Bryggen. Map: A. Seither, NGU.

Temperature variations can be used as an indicator for groundwater-flow rates. Seasonal groundwater-temperature variations tend to decrease with depth and show a delayed response to the air temperature. The temperature variations of the groundwater within the archaeological deposits show a delay of about two months compared to temperature variations of the air. The variations in the old seabed underneath the deposits are considerably smaller and there is a delay of about four months. At selected locations, detailed groundwater temperatures have been measured in vertical profiles through the unsaturated and saturated zones. For a detailed description of the results of these temperature measurements the reader is referred to chapter 7. Effects of mitigation on groundwater temperatures

Replenishment of the groundwater by shallow infiltration may affect groundwater temperatures. They may increase locally due to infiltration of (warmer) rainwater and by rerouting groundwater from pumping wells on the inside of the sheet piling to the I/T-system. During summer, the effect may be reversed. Thus far, the accumulated monitoring series are too short to draw conclusions on the effects of mitigation measures on the groundwater temperature. The main heat source, namely buildings and other manmade structures, is still present. As long as they are not heat insulated, they will continue to release heat to the adjacent ground. The effects of temperature on decay rates are discussed in chapter 7.



Future groundwater-temperature monitoring

Monitoring of groundwater temperature should be continued for several more years in order to retrieve sufficient data to carry out an assessment of the impact of the mitigation works. Temperature data are also necessary for the calibration of oxygen measurements, the most direct indicator of decay, see also chapter 6.

GROUNDWATER MODELLING

In order to improve our understanding of the hydrogeological system, to quantify the water balance and to identify the factors influencing preservation conditions, a 3D subsurface framework model and a numeric

groundwater model were constructed using GSI3D and FeFlow respectively.<sup>162</sup>

The chosen model area includes the catchment area behind Bryggen. Based on the terrain model created in GSI3D, on borehole data, known construction depths of buildings, as well as archaeological descriptions, a numeric model with 10 distinct layers was constructed. The hydraulic properties of the respective layers were initially based on values taken from relevant literature, along with descriptions of the individual strata in the monitoring well boreholes and particle-size analyses of soil samples. During later phases of the modelling, these parameters were changed in stages after verification against monitoring values. The model's mesh size was defined to be finer in the areas of interest, such as the

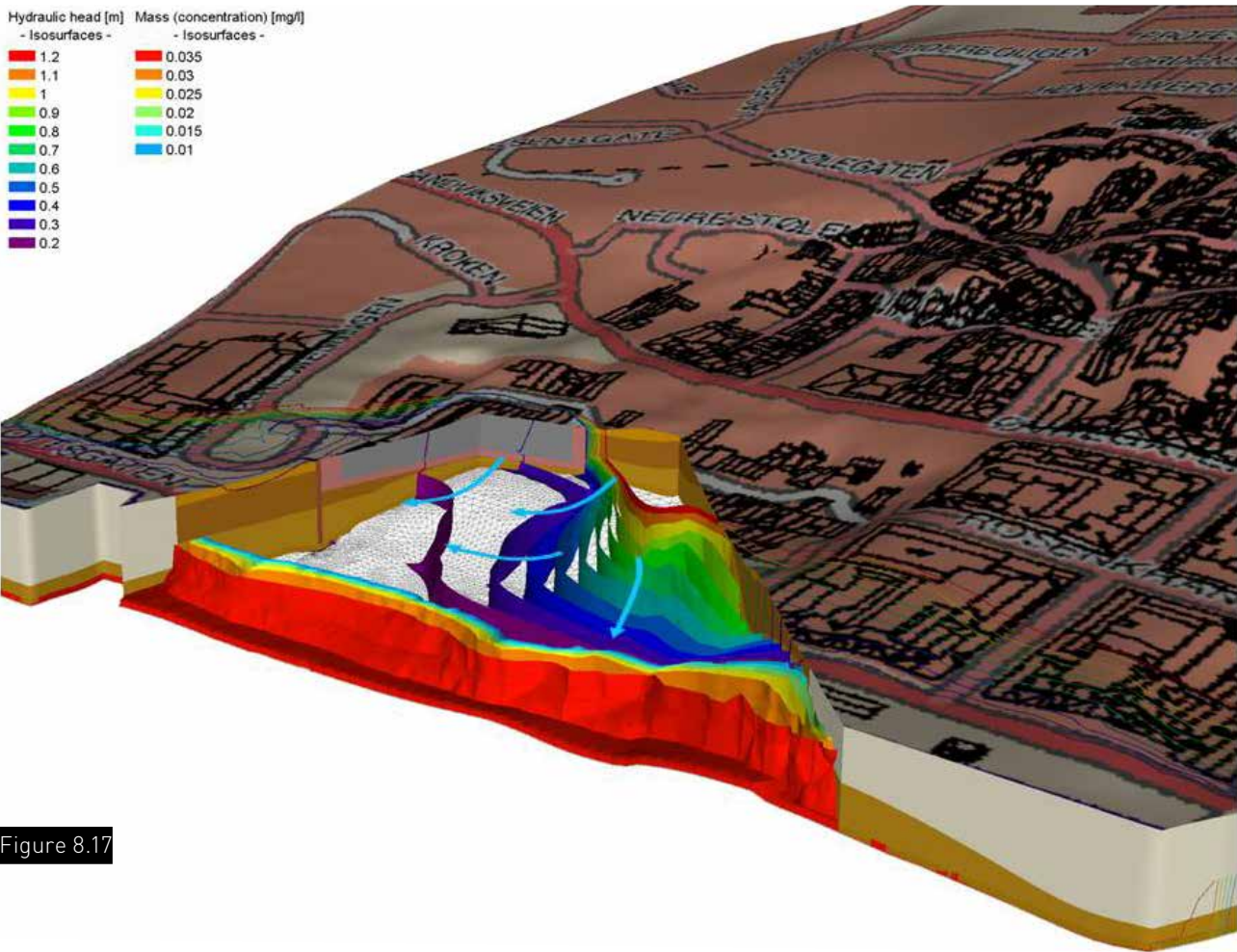


Figure 8.17

Figure 8.17 3D view of the groundwater model of Bryggen. Map: J. de Beer, NGU.

sheet piling and the drainage systems. Tidal variations and saltwater in the harbour, daily precipitation and known drainage systems served as boundary conditions. Fig 8.17 shows a 3D visualization of the groundwater model (FeFlow) with indication of flow directions.

Results

The numeric groundwater model helped us to understand spatial and temporal hydrogeological variations at Bryggen and adjacent areas, as well as their potential impact on the in-situ preservation of archaeological deposits.

The impact of the sheet pile wall and the drainage system around the hotel on Bryggen's groundwater conditions became very clear. The most vulnerable parts of the area could be identified. The model proved to be a useful

tool for finding appropriate mitigation measures and for finding the optimal strategy and locations for monitoring.

Fig. 8.7 shows the average lowest annual groundwater levels. By subtracting the groundwater levels from the surface levels, one obtains the calculated thickness of the unsaturated zone, shown in Fig. 8.18.

In combination with the recorded thickness of the archaeological deposits, risk maps can be created that show the decay potential in 3D. Figure 8.19 shows a 3D section view combined with the average lowest annual representative water table. Locations where the archaeological deposits (dark brown) are positioned above the water table are at risk of accelerated decay.

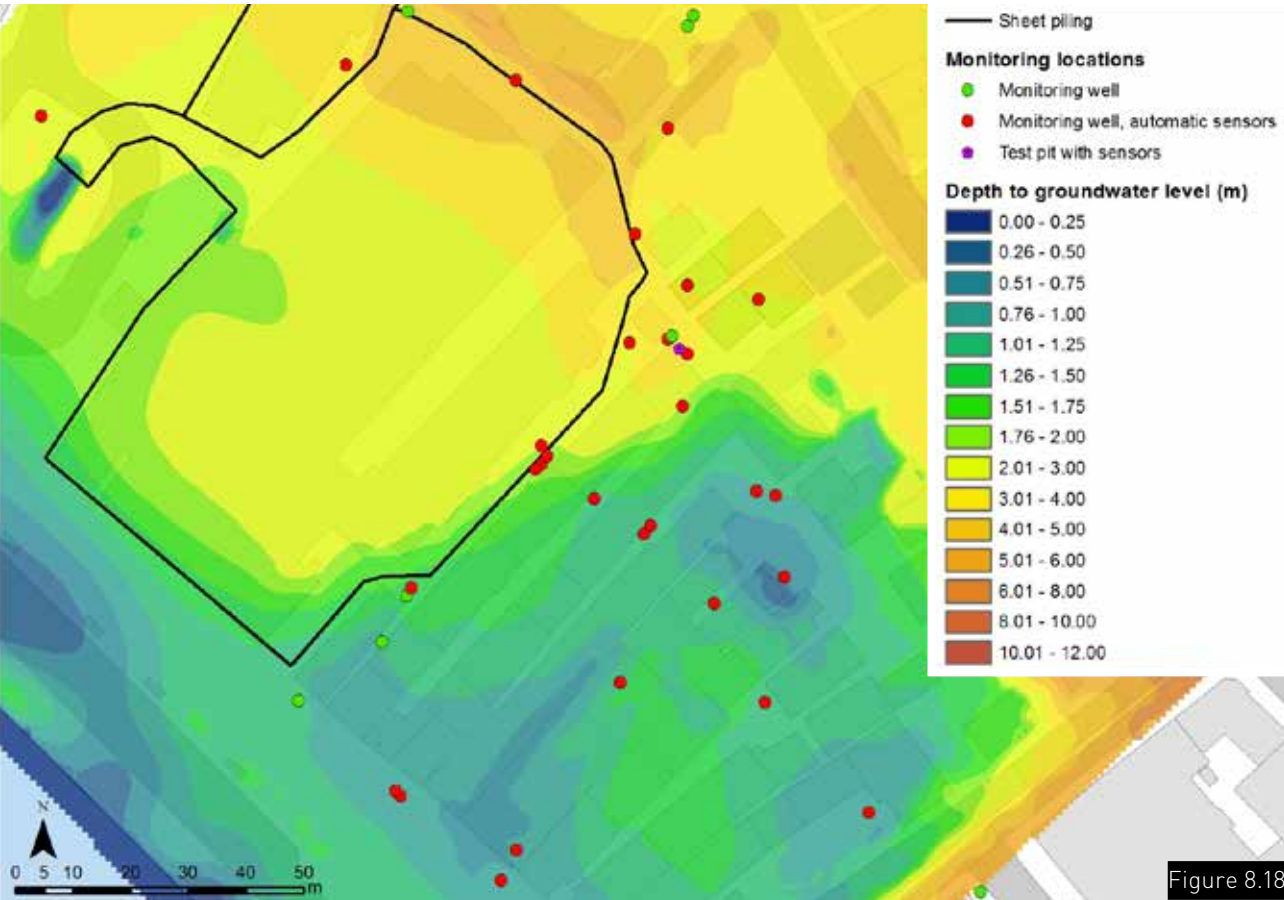


Figure 8.18

Figure 8.18 Calculated thickness of the unsaturated zone, during a representative dry period. Map: J. de Beer, NGU.



# CONCLUSIONS AND RECOMMENDATIONS

Even though Bergen is known for being a very wet city, manmade structures such as drainage systems, sheet pile walls, and the redirection of rainwater into municipal stormwater systems can locally cause a lack of water in the subsurface. The lack of water has caused the decay of protected archaeological deposits and subsidence of buildings.

The key success factor for safeguarding the Bryggen WHS lies in a more sustainable management of the urban water balance, including groundwater. As in other cities around the world, Bergen’s traditional stormwater management has long focused on securing safe floodpaths and on transporting excess water as quickly as possible to surface-water systems (and ultimately to the sea). The situation at Bryggen has shown, however, that a lack of water can be just as damaging as an excess. The main cause of the threatening groundwater situation was caused by urban development in the late 1970s, a development that had been carried out in line with traditional urban-drainage philosophy, without realizing the potential negative consequences it could have on the wider surroundings. In addition, the same ‘traditional’ urbanization in the surroundings of Bryggen led to steadily more sealed surfaces, piping of previously open waterways, reworked ground material and more direct transport of rainwater to mixed sewage systems. All these measures have clearly affected the water balance at Bryggen in a negative manner and contributed to an unbalanced situation with falling groundwater levels, decay of archaeological deposits, and subsidence.

Safeguarding Bryggen for the future will require continued monitoring of groundwater levels, temperature and quality. These are parameters key for assessing changes in the preservation conditions in the archaeological deposits and the related risks of subsidence of the ground and buildings. Chapter 12 describes the monitoring and maintenance plan for Bryggen in more detail.

Bergen municipality was the first municipality in Norway to adopt a more sustainable water management policy. Still, this policy is mainly focused on handling urban stormwater at the ground surface, and not focused on long-term consequences for the urban water balance as a whole. The Bryggen project has shown that this policy needs to

be extended to include the subsurface and groundwater, to foresee and avoid long-term ‘prowling’ damage by e.g. decay of organic material and subsidence. Systematic groundwater monitoring and three-dimensional mapping of the subsurface properties are essential elements in a more sustainable water-management practice that includes the whole water-balance system. It is therefore recommended that systematic groundwater monitoring and hydrogeological mapping of the subsurface are given due consideration in all urban water-management systems in Norway and abroad.

At Bryggen, the archaeological deposits were of primary interest. However, the complex processes that determine their state of preservation could not be understood without seeing the surrounding hydrogeological and chemical system as a whole. In order to find appropriate measures that reduce decay and subsidence, the investigation, mapping and monitoring of natural, underlying ground materials were just as important as the analyses of the archaeological deposits itself. The Bryggen project has illustrated that this holistic approach will be necessary also at other sites where in-situ preservation of archaeological deposits is considered or planned.

Bryggen’s situation is complex, and as such it required a multidisciplinary approach to solve its problems and to avoid pitfalls. The chosen protective and mitigation measures for archaeological deposits that are based on improvement of the water-management system clearly have multiple benefits. Although the water-management systems applied at Bryggen, such as swales, infiltration facilities and permeable pavements, may need particular adjustment to protect archaeological deposits, they are originally designed to achieve more sustainable stormwater management. Reducing peak flow, increasing capacity in the existing sanitation system, improving water quality and (green) aesthetic values are important aspects, while protection of archaeological deposits is an additional benefit. Real sustainable urban development, including archaeological heritage preservation, combines a variety of functions and optimizes multiple benefits. An effective collaboration between professionals from many disciplines is necessary to identify those benefits and ensure success.

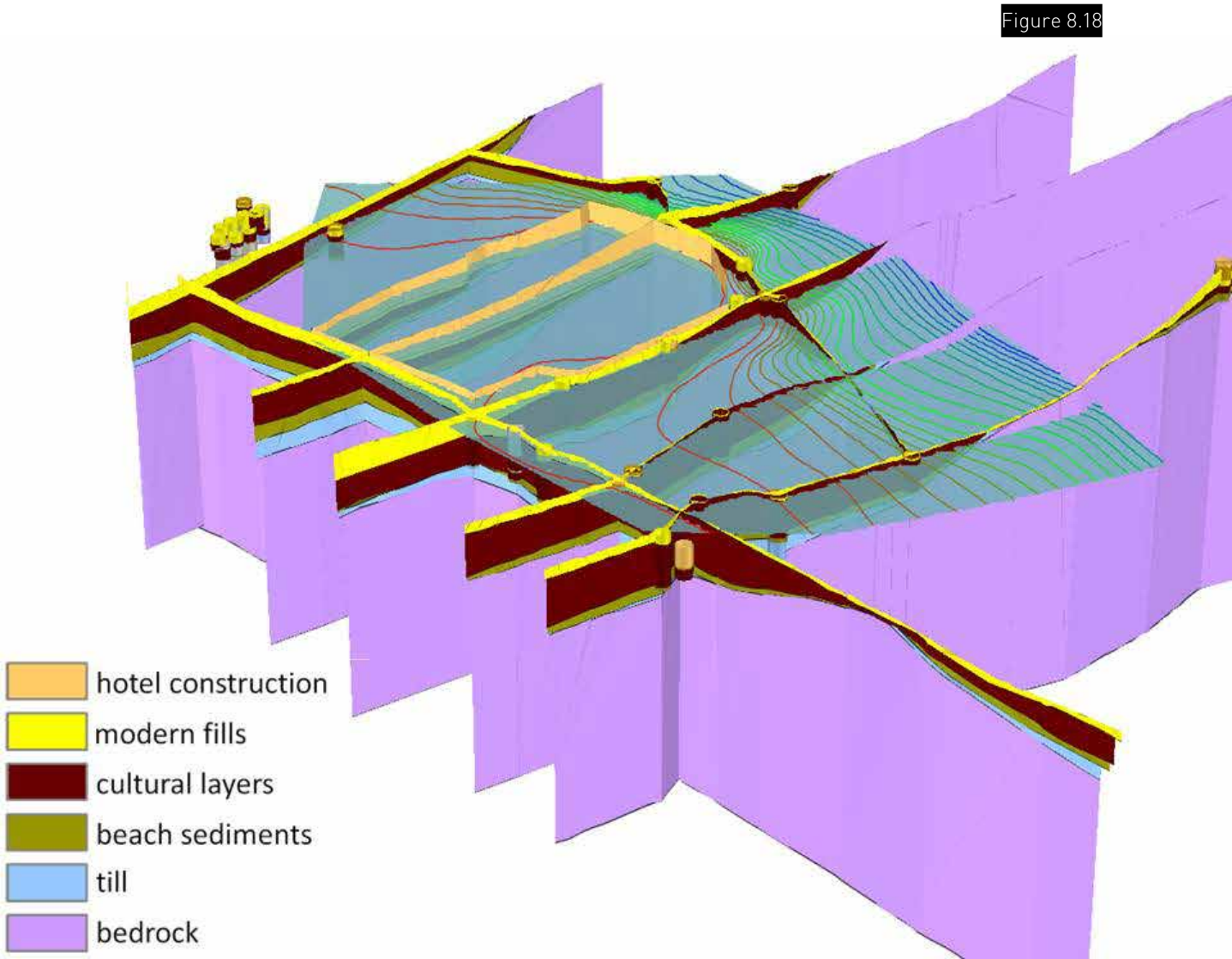


Figure 8.19 3D section view with a representative annual-low level of the watertable. J. de Beer et al. 2012.



09

## GROUNDWATER LEVEL RESTORATION

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Kevin J. Tuttle  
Norconsult AS



## INTRODUCTION

After the construction of the hotel with its underground parking area kept dry by groundwater pumping, monitored subsidence of the surface and buildings has occurred over a decade. Investigations concluded that groundwater drawdown under the hotel resulted in the intrusion of oxygen into the soil, causing accelerated decay of the organic constituents in the archaeological deposits, and consequently the subsidence of the ground and buildings.

The goal of the project has been to reduce the rate of subsidence in the Bryggen area to 1 mm/year or less. To accomplish this goal, the groundwater level below the surface needed to be raised to a general level of about 1 m below the ground surface. Restoring the groundwater level to 1 m below the ground surface would reduce the rapid decay of the organic matter, thereby reducing the subsidence.



Figure 9.1

Figure 9.1 Colour dye to be added to borehole with white cap, in colour tracer test. The tracer was captured with activated carbon passive samplers in nearby monitoring wells. Photo: L. Basberg, Norconsult AS.

## LOCAL SUBSURFACE CONDITIONS INFLUENCING GROUNDWATER FLOW AND LEVEL

### Past conditions

Natural conditions at Bryggen before modern infrastructure was established consisted of a waterfront along the northeastern shore of a brackish-water harbour, with several freshwater rivers and streams flowing from the surrounding hills. These streams and rivers supplied the natural and anthropogenic deposits between the hillsides and shoreline with ample water to keep the groundwater level near the ground surface. Modern city infrastructure has changed that supply of surface water, and much of it is now drained quickly out to the sea, reducing the supply for infiltration into the groundwater resource.

### Present conditions

Present conditions in modern cities usually consist of several drainage schemes that either reduce water infiltration into the subsurface and/or effectively transport groundwater away from the upper subsurface. These drainage schemes are either meant to drain groundwater, like pumps under buildings to drain groundwater below cellars and underground garages, or are a result of modern infrastructure, like pipe and cable ditches filled with permeable fill transporting groundwater above the bottom of the ditch to lower elevations.

In the present case at Bryggen, there are several conditions that are influencing the groundwater level. The parking area below the hotel at Bryggen requires the groundwater level below the hotel to be drained to a level of 0.80 metres above sea level (masl.), due to construction limits. The garage has been excavated to a depth that has exceeded the thickness of the archaeological deposits and natural deposits on the hill-end of the hotel, meaning that excavation has also had to penetrate the bedrock surface. Groundwater from the permeable bedrock fractures and from the deposits has drained through and beneath the sheet piling surrounding the hotel and into the drainage system beneath the hotel.

The drainage has resulted in the reduction of the groundwater pressure and level, both in the underlying bedrock fractures and in the upper archaeological deposits near the surface. Since the major portion of the present subsidence at Bryggen is due to the decay of the organic archaeological deposits near the surface, focus in this project has been to re-wet this upper area of the ground to strongly reduce the rate of decay. This has meant that tasks have focused on creating an upper groundwater level, or a “hanging groundwater resource”. In order to raise the groundwater level at this elevation, groundwater flow and drainage through the sheet piling to the drainage system needed to be investigated and mitigated.

## FIELD SURVEYS INVESTIGATING GROUNDWATER FLOW DIRECTIONS

Field surveys were conducted to determine flow directions of groundwater near the sheet piling, measure the difference in groundwater pressure in the underlying natural sediments, bedrock fractures and in the upper archaeological deposits, as well as to document the effects of surface infiltration on the groundwater level in the archaeological deposits. These investigations have aided in optimizing the mitigation work to restore the groundwater level in the Bryggen area.

### Tracer test near sheet piling

Initially, tracer tests were aimed at registering the rate of groundwater drainage through the sheet piling. The tracer tests consisted of several colour dyes added to a few monitoring wells, and passive samplers (activated carbon) were used to detect the paths of the tracers in other monitoring wells. Surveys showed however, that in the area the tracers were released, groundwater flow was then predominately parallel to the sheet piling towards draining ditches for potable water and sewage pipelines. These ditches have generally drained to the sea in front of Bryggen. This result indicated that it wasn’t just the drainage through the sheet piling to the hotel drainage system that extracted the groundwater.<sup>163</sup> Also shallow horizontal groundwater flow via other near-surface infrastructure ditches needed to be dealt with before the project could be successful in restoring the groundwater level.



With the results of the tracer test along with other observations, the project could highlight the need for mitigation work to stop drainage of groundwater along the outer walls of the sheet piling, within the infrastructure ditches and manholes, as well as through leaky surface-water drainage piping and sewage lines. Holes in the sheet piling were also attended to in order to reduce groundwater flow under the hotel. These tasks took approximately one year, and have resulted in much less groundwater being drained quickly to the sea, aiding in restoring the groundwater level.

Groundwater pressure-levels at different depths below the surface

A data compilation of the monitoring wells at Bryggen (see chapter 8) showed that wells monitoring the lower deposits and bedrock groundwater pressures having often lower groundwater levels than the higher groundwater levels in the overlying archaeological deposits. This was interpreted as an effect of the drainage from under the hotel primarily coming from under the sheet piling and from the exposed bedrock under the hotel. There has been, and still are, a few sites that have groundwater drainage directly from the upper archaeological deposits through holes in the sheet piling. Although the decrease of groundwater pressure below the lower deposits and in the bedrock may have caused a certain amount of subsidence, the high rate of existing subsidence has been deduced to result from the fast rate of organic decay of the upper archaeological deposits. Activities have therefore been focused on raising the groundwater level within the upper archaeological deposits by infiltrating water near the surface in order to sufficiently reduce the rate of surface subsidence.

Infiltration tests

In addition to the infiltrating-beds and the rainwater garden in the upper portion of Bryggen (see chapter 10), several stepwise infiltration/transport (I/T-) systems in the form of ditches with progressively lower levels (see chapter 8) have been established around the hotel. These I/T-systems supply water to the upper archaeological deposits, where the groundwater has been the lowest, by directing rainwater from eave troughs to the ditches in periods with precipitation, and with groundwater from below the hotel during dry periods. Drinking water may be utilized when the prior sources are not sufficient.

Tests were conducted to register the effectiveness of the I/T-systems and the amount of water needed to meet the project’s groundwater replenishment goals of approximately 1 m below ground elevation.<sup>164</sup>

The tests revealed additional drainage holes in the sheet piling, and other preferential flow paths that the water took away from the area of interest. Precipitation during the test period (spring-summer 2014) was unusually low too, making it difficult to interpret if the system was adequate. The amount of water needed initially was in excess of available water for the restoration of groundwater levels. Additional excavation made it possible to seal leakage points through the sheet piling, and adjustments were made to the infiltration scheme.

The latest measurements of the groundwater level during the activities to restore the groundwater level are in the following paragraphs illustrated and compared with the project goals. See also results from individual monitoring wells in Chapter 8.

GROUNDWATER REPLENISHMENT

Through the infiltration tests conducted in the field, it is evident that the subsurface contains other drainage paths than just the de-watering below the hotel. In the area between the Bryggen Museum and the Schøtstuene buildings, groundwater appears to drain to lower levels towards the west. It is also apparent that other areas drain the groundwater quicker than others due to variations in soil permeability, in addition to quick changes in ground elevation, making a goal of a groundwater level 1 m below the surface in some local areas impossible to reach and in fact irrelevant, as this would cause flooding issues at neighbouring, lower-lying areas.

Infiltration requirements

The current infiltration system consists of the upper groundwater being recharged with rainwater from the nearby roofs. The eave troughs are channelled to the I/T-system along the sheet piling (see Chapter 8 for illustrations), while excess rainwater is drained to the municipal drainage system to the sea. This system works well during rainy periods, but Bergen has experienced several spells with prolonged dry periods the last few years, possibly due to effects of long-term climate change.

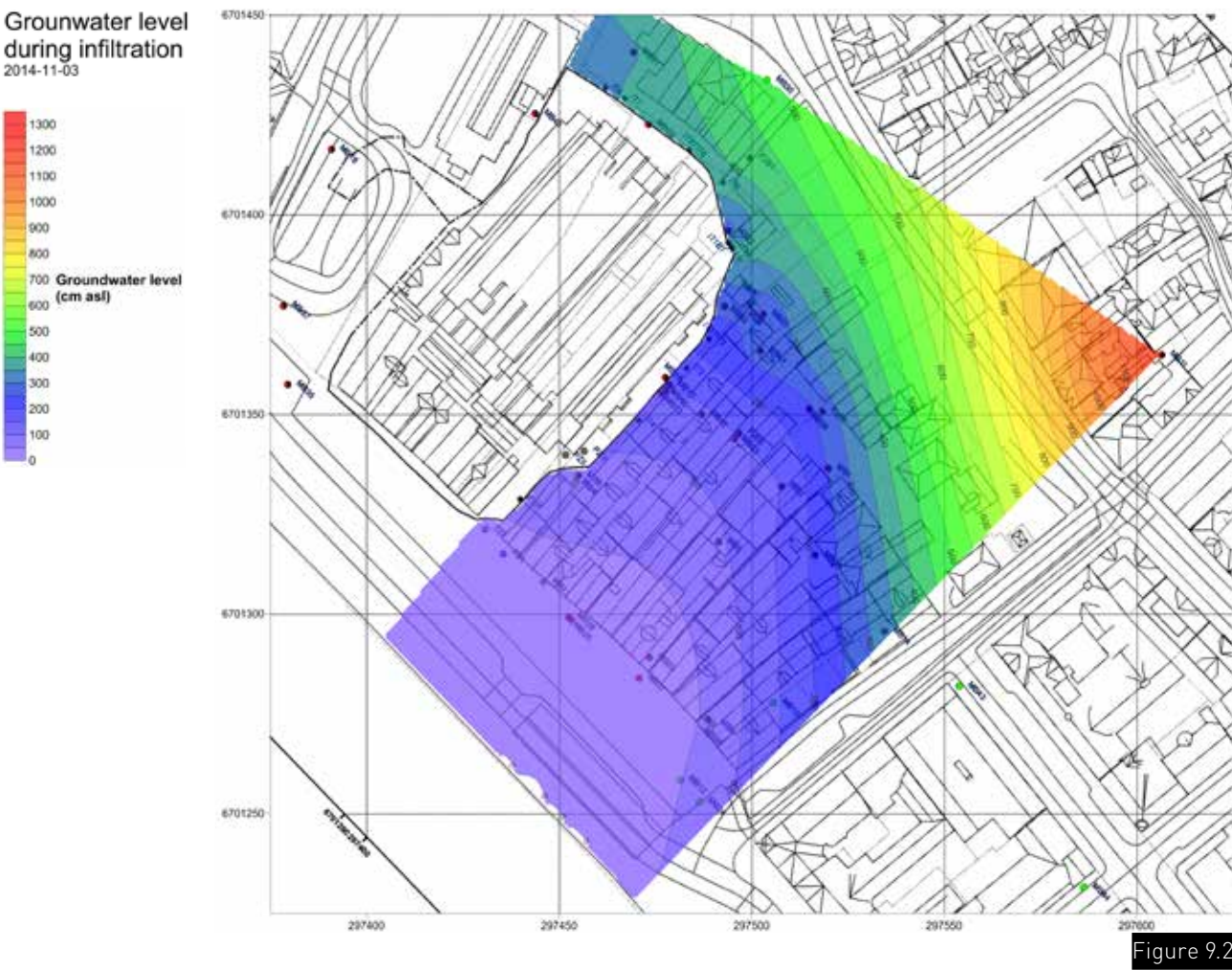


Figure 9.2

During dry periods, it is necessary to supply the infiltration ditches of the I/T-system with additional volumes of fresh water. Since the groundwater below the hotel is not to rise above 0.8 m above sea level, the excess fresh groundwater has previously been drained to the sea. The project has installed two groundwater wells inside the sheet piling, which can pump the excess groundwater to the I/T-system and the infiltrating rainwater garden at the upper end of Bryggen. In addition to the excess deep groundwater from under the hotel, it is possible to recharge with municipal drinking water when needed.

System vulnerability

The water management system at Bryggen is vulnerable to long periods of dry weather. The main sources of water are from precipitation and from excess groundwater, fed by precipitation. At present, the only other source of water to infiltrate the upper groundwater level is from the municipal

water supply. Other sustainable sources of water have been considered, including channelling of excess water from the Skansendammen reservoir. The alternative sources need to be sustainable, also during dry periods.

Meeting groundwater target-levels

The project has been based on a step-wise progression, initiating mitigation works, monitoring groundwater-level response, then further mitigation, depending on results from previous tasks and newly identified leakages in the system. The groundwater level has been rising for each of these iterations.

Figure 9.2 Groundwater level in upper deposits at Bryggen on the 3rd of November, 2014. This groundwater map illustrates the elevation of the water table in cm above sea level. Map: L. Været, Norconsult AS.



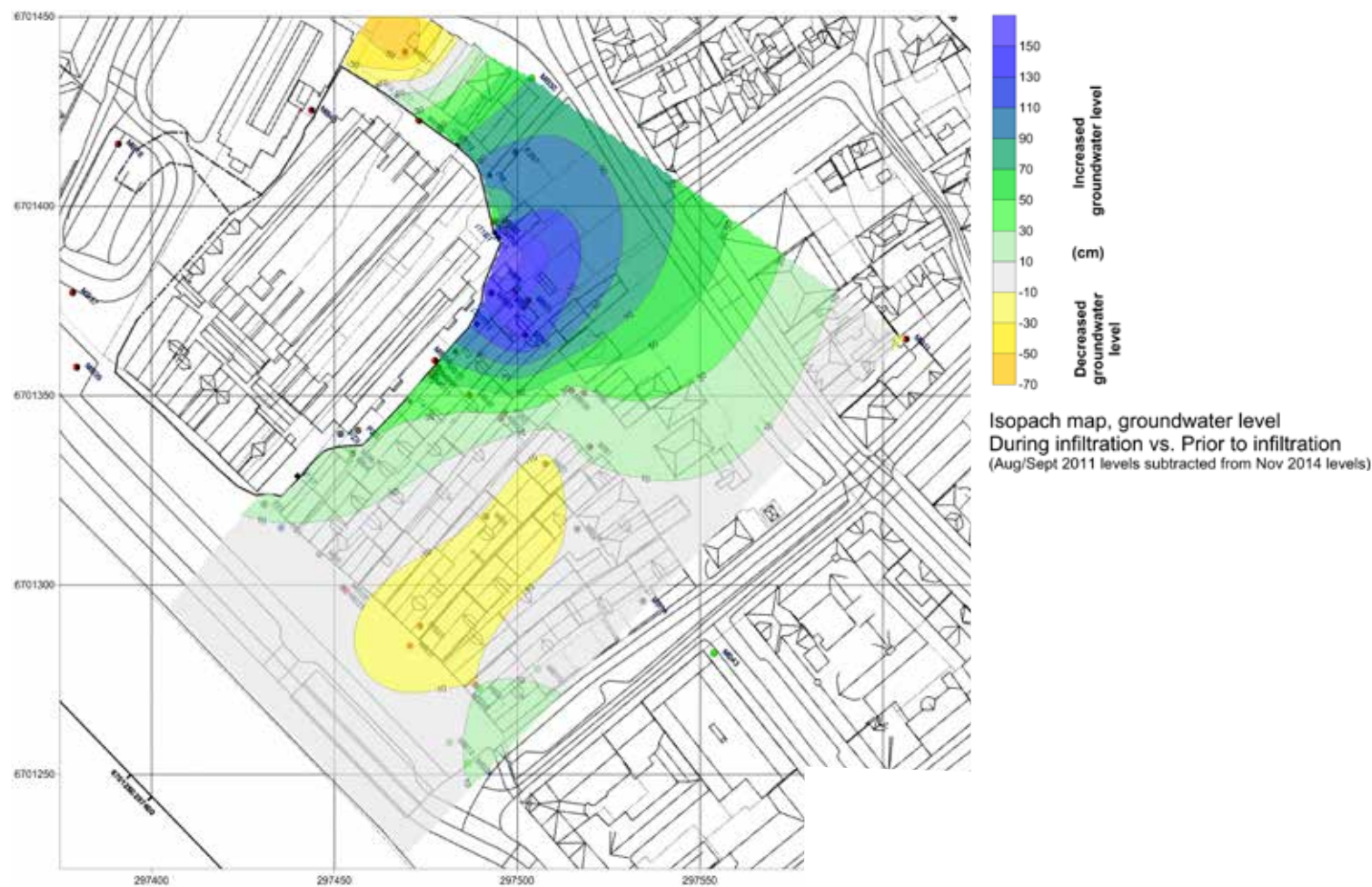


Figure 9.3

Testing the water management system was done during a rather long dry period, illustrating the need for additional water from excess groundwater from under the hotel, as well as from the municipal water supply in order to meet goals under such conditions. Bergen has in the past had an average precipitation of 2,250 mm/yr. This volume distributed throughout the year does not accumulate to the amount needed to sustain the required groundwater

Figure 9.3. Difference between groundwater level in August 2011, prior to mitigation works, and in November 2014, after the groundwater replenishment. Green and blue shades represent areas with groundwater levels higher than when mitigation works commenced, while yellow shades represent areas where groundwater levels are lower than when mitigation works were initiated. The lower levels are due to 2014 having been a drier year than 2011. Map: L. Været, Norconsult AS.

level. Groundwater from below the hotel is needed to replenish the upper groundwater level.

Groundwater-level measurements taken on the 3rd of November 2014 indicate that the groundwater level has nearly risen to the designated project goal level.

Areas that have not reached the designated elevation lie within approximately 40 cm of the set goal. This result may be adequate for the initial project goal of reducing the annual subsidence rate to less than 1 mm. It can be argued that with the groundwater level only 40 cm below the set elevation, capillary forces in the soil/ archaeological deposits may be sufficient to keep the organic deposits water saturated and strongly reduce the oxidation and decay of the archaeological deposits, and therefore also strongly reduce the subsequent surface subsidence.



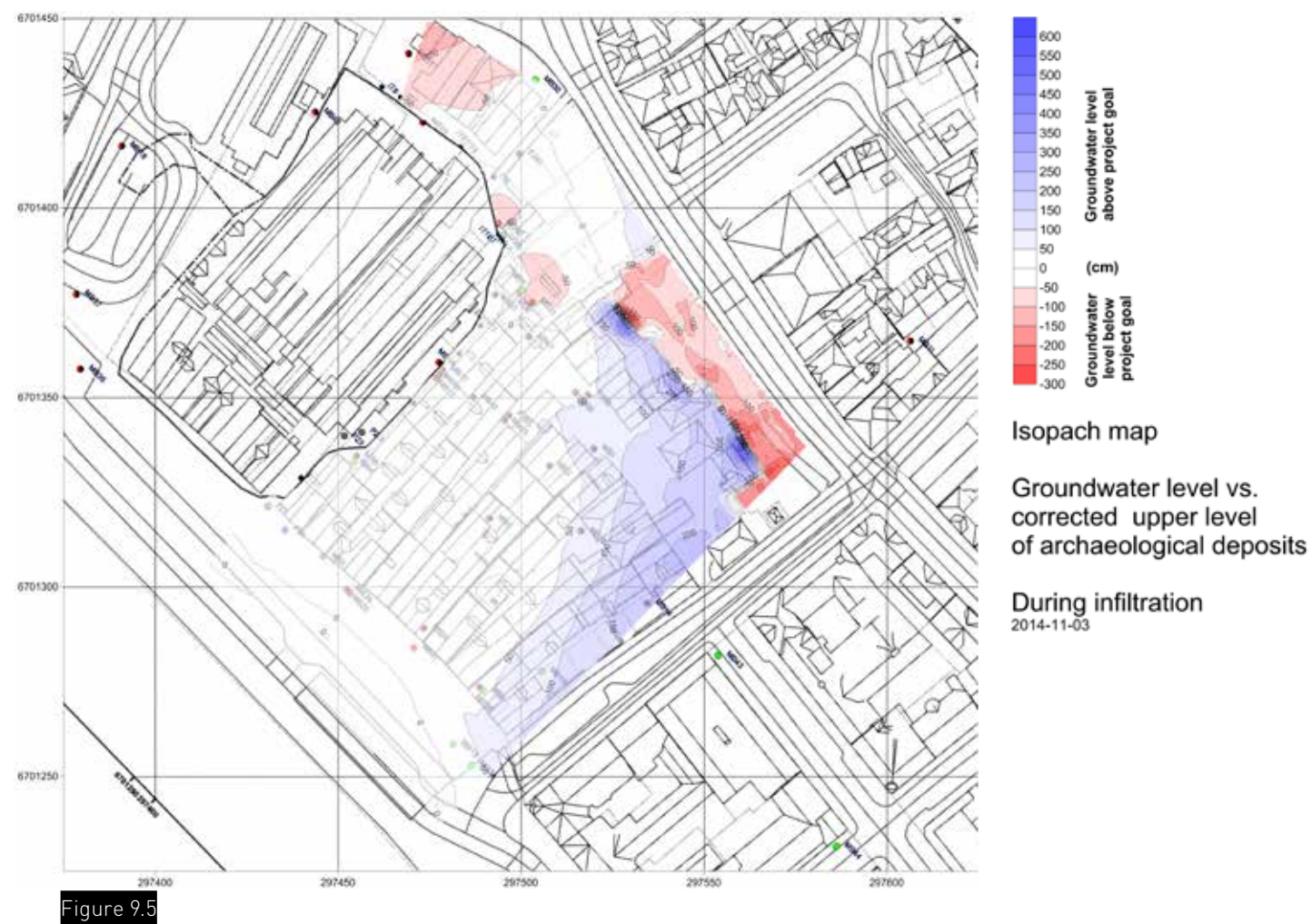
Figure 9.4

The I/T-system will aid in keeping groundwater levels high, even in periods with little or no precipitation. This will hold the moisture in the archaeological deposits high, even if in a natural setting these conditions would have lowered the groundwater level, and allowed for periods with greater decay.

In areas where the terrain has been filled in with material above the organic archaeological deposits, the distance between the groundwater level and elevation 1 m below the terrain may give an incorrect representation of the saturation level of organic deposits. Fig. 9.5 below has been created to show our interpretation of the upper organic level of the archaeological deposits, after discussions with Rory Dunlop.<sup>165</sup> The upper elevation of the organic archaeological deposits has been estimated to be between 4 and 5.25 masl in the area up-gradient of the hotel, with a surface gradient ratio of 1:20.

Figure 9.4 Difference in groundwater levels and the project's target levels for the groundwater replenishment, based on measurements taken the 3rd of November, 2014. Largest divergence from target levels is in areas with irregular terrain elevations. Map: L. Været, Norconsult AS.





## RECOMMENDATIONS FOR FURTHER MITIGATION

Continued work should be focused on solving a sustainable water supply to the I/T-system so that a municipal water supply is not depended upon in extended dry periods. Bergen has several old surface reservoirs that could be connected to the I/T-system. There are plans to excavate several bedrock tunnels and caverns in the near future uphill from Bryggen. The possibility of channelling eventual drainage water from these structures could be evaluated for infiltration at Bryggen, but such drainage may also affect the lower bedrock groundwater pressure/level at Bryggen. Such drainage should not occur, or be limited to a minimum.

Continued monitoring of the oxidizing conditions in the archaeological deposits as well as subsidence measurements should register and conclude if the project results have accomplished its initial goal of reducing the rate of subsidence to less than 1 mm/yr. This monitoring will require several years before a conclusive finding can be presented.

Figure 9.5 Difference in groundwater level and the interpreted upper surface of the organic archaeological deposits at the upstream end of the project area.  
Map: L. Været, Norconsult AS.





# 10

## STORMWATER QUALITY AND SUSTAINABLE URBAN DRAINAGE MANAGEMENT

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Figure 10.1

No	Name	District	Category	Remarks
1	S2	Øvregaten	Road (roofs connected)	In Øvregaten the traffic load is between 5000-10 000 vehicles/day.
2	S3	Wesenbergsmauet	Roof	
3	S4	Nikolaikirkeallmenning	Roof	
4	S6	Koren Wibergs Plass	Road (roofs connected)	0-350 vehicles/day

Figure 10.2

## INTRODUCTION

Urbanization changes the hydrology and alters water balance. One of the key challenges in heavily developed urban areas is the lowering of groundwater levels due to lowered infiltration rates as a result of increased impervious surfaces. Within urban areas there are places with archaeological deposits with a special need for sustainable urban stormwater management. The management of these sites is complex and requires a multi-disciplinary approach in order to achieve long-term preservation of vulnerable archaeological deposits.<sup>166</sup>

Our urban landscape has formed over generations and our modern city infrastructure is often built on and in extensive archaeological deposits. Depending on the natural environment, the archaeological deposits at many sites may consist of highly organic, naturally degradable strata. The conditions for preservation have been shown to be strongly dependent on both water quality and the presence or absence of groundwater in particular. Lowering of groundwater levels can have a large negative impact, causing an increased supply of oxygen to the deposits and accelerating the decay of the organic material.<sup>167</sup> Intensive and widespread monitoring of groundwater levels and groundwater flow has been conducted at Bryggen, as well as classification of the preservation conditions in the medieval layers.<sup>168</sup> Re-establishing the natural water balance in such a system is the most sustainable way to create good conditions for preservation.

The Directorate for Cultural Heritage in Norway is committed to in-situ preservation of archaeological deposits as far as possible. The Valletta Treaty obliges the signatory states to try to ensure ‘the conservation and maintenance of the archaeological heritage, preferably in situ’. This includes all remains, objects and any other traces of humankind from past times. The municipality of Bergen has set goals to use stormwater-handling methods that do not harm the environment, buildings and constructions. They state that Low Impact Development measures (LID, or Best Management Practices, BMP’s, or Sustainable Urban Drainage Systems, SUDS), such as rainwater gardens or bioretention, swales, wet and dry ponds and wetlands, should be utilized where possible.

Figure 10.1 The catchment area upstream from Bryggen.<sup>169</sup> Map: F. Boogaard, TAUW.

## Strategy

Re-establishing the natural water balance to create good conditions for preservation at Bryggen requires the following steps:

- review the present situation
  - water quantity: how much water can and do we have to infiltrate to keep the archaeological deposits saturated?
  - water quality: the quality and characteristics of stormwater in the Bryggen area
- determine the targets for the future situation
  - compare quantity and quality requirements and international approaches
  - select and estimate the required performance of SUDS
- implementation and maintenance of the desired situation
  - monitoring and maintenance plan for the future

## MONITORING (STORM-)WATER

Water should be stored in order to ensure high groundwater levels during dry periods. Paved areas (roads and roofs) should be connected to this storage in order to infiltrate as much water as possible. For this reason the quality of the water from roads and roofs had to be checked. This section will focus on the measured stormwater quality and the suitable types of sustainable urban drainage systems.

### The monitoring area

The land use in the watershed consists of a city block layout with narrow passageways between the blocks and roads connecting the blocks together. The total area is 4.3 ha. The quality of the stormwater was monitored and the characteristics of the stormwater were determined (particle-size distribution, and the distribution of pollutants to suspended solids). Four sampling points in the watershed were used (Figs. 10.1 and 10.2 opposite page):

- two road sites that were later combined to one site
- two roofs (one tile roof and one slate roof)

Fig 10.2 shows details about the sampling points.

Figure 10.2 Sampling points.<sup>170</sup> Table: F. Boogaard, TAUW.





Figure 10.3:1



Figure 10.3:2



Figure 10.3:3



Figure 10.3:4

Detailed knowledge on site-specific stormwater quality and behaviour by measurements and comparison with international data is essential for the choice of SUDS, at least when water quality is a priority issue. The next information required is:

- Quality of stormwater (concentrations of pollutants compared to international data)
- Characteristics of stormwater (dissolved and pollutants bound to suspended solids in stormwater)
- Behaviour of stormwater (particle-size distribution)
- Basic information on the performance of SUDS (hydraulic performance and removal efficiency).

Figure 10.3:1-4 Photo, sampling points 7.2.2013. Photos: F. Boogaard, TAUW.

### Sample collection

The field sampling took place from February through April 2013. Early spring in a cold coastal climate is a challenging sampling period, as rainfall can often turn into snowfall. In the end four precipitation events were sampled over a three-month period, resulting in a total of 13 samples. The sampling took place at four different sites:

1. Øvregaten S2
2. Wesenbergsmauet S3
3. Nikolaikirkeallmenning S4
4. Koren Wibergs plass S6

The sampling points are considered to be representative for the water quality expected from the area.

Parameter	Unit	Bryggen	Bryggen	Worldwide (Bratieres et al., 2008)	Dutch (Boogaard) a	USA (NSQD) 2004b	Europe/Germany (ATV database, Fuchs et al., 2004)d
		mean	median	mean	mean	median	median
Pb	ug/l	36	22	140	18	6	12
Zn	ug/l	434	153	250	102	60	73
Cu	ug/l	111	11	50	19	11	12
NO <sub>3</sub>	mg/L	1.1	0.6				
SO <sub>4</sub>	mg/L	12.7	11.4				
Cl	mg/L	213	30		18.3	11.0	

Figure 10.4

### Concentrations of pollutants compared to international data

The results (median and mean values) of the measurements are shown in Fig. 10.4, the focus of the search for effective stormwater treatment at sites like Bryggen is mostly on micro-pollutants such as the heavy metals copper, zinc and lead. In Fig. 10.4 the data from Bryggen is compared to several databases on stormwater quality drawn from other countries. From the available literature and data it can be seen that the quality and characteristics of stormwater can differ strongly per country, location, and even within one stormwater event. The characterization of stormwater quality with regard to contaminants (particle-size distribution, degree of binding to suspended solids etc.) is important to assess which SUD is required.<sup>171</sup>

From the Fig. 10.4 can be derived that the median concentrations found at Bryggen are within the wide variety of concentrations found in the world. However, we see that due to some high individual measurements the mean concentration of copper and zinc can be on the high side. Note that in some databases the concentrations of pollutants are measured in the sewerage system instead of directly at the surface as at Bryggen.

### Characteristics of stormwater and SUDS

Detailed knowledge of the characteristics of stormwater is important for the determination of the implementation of SUDS. The ability of pollutants to bind with suspended solids will enable these pollutants to be trapped by

Figure 10.4 Bryggen and international stormwater-quality data from residential areas in USA, Australia and Europe.<sup>172</sup>

sedimentation and filtration. Comparing filtrated and infiltrated heavy metal samples at Bryggen shows that most of the micro-pollutants are particle-bound (for copper and zinc: 64 and 79 % respectively).<sup>173</sup> Particle-size distribution in the stormwater showed considerable variation, but in stormwater from the roads the particle sizes are in the range of findings in international literature.

### Conclusions regarding stormwater

SUDS should be implemented to store as much water as possible in the limited space of Bryggen. Since the paved areas upstream will be connected to this storage, the quality of the stormwater has been analyzed in order to choose the right SUDS with optimal efficiency for the removal of possible pollutants.

From the findings it is recommended to capture fine sediment (< 63 um) in order to have a high removal efficiency by SUDS on micro-pollutants. The characteristics of stormwater tell us that we should focus on SUDS with the capability of filtration and absorption of dissolved and particle-bound pollutants, rather than using sedimentation only.

## SUSTAINABLE URBAN DRAINAGE SYSTEMS (SUDS)

The appropriate use of sustainable urban drainage systems (SUDS) can reduce urban surface-water flooding, reduce the impact of urban stormwater pollution discharges on receiving waters, and contribute to maintaining high groundwater levels in dry periods.

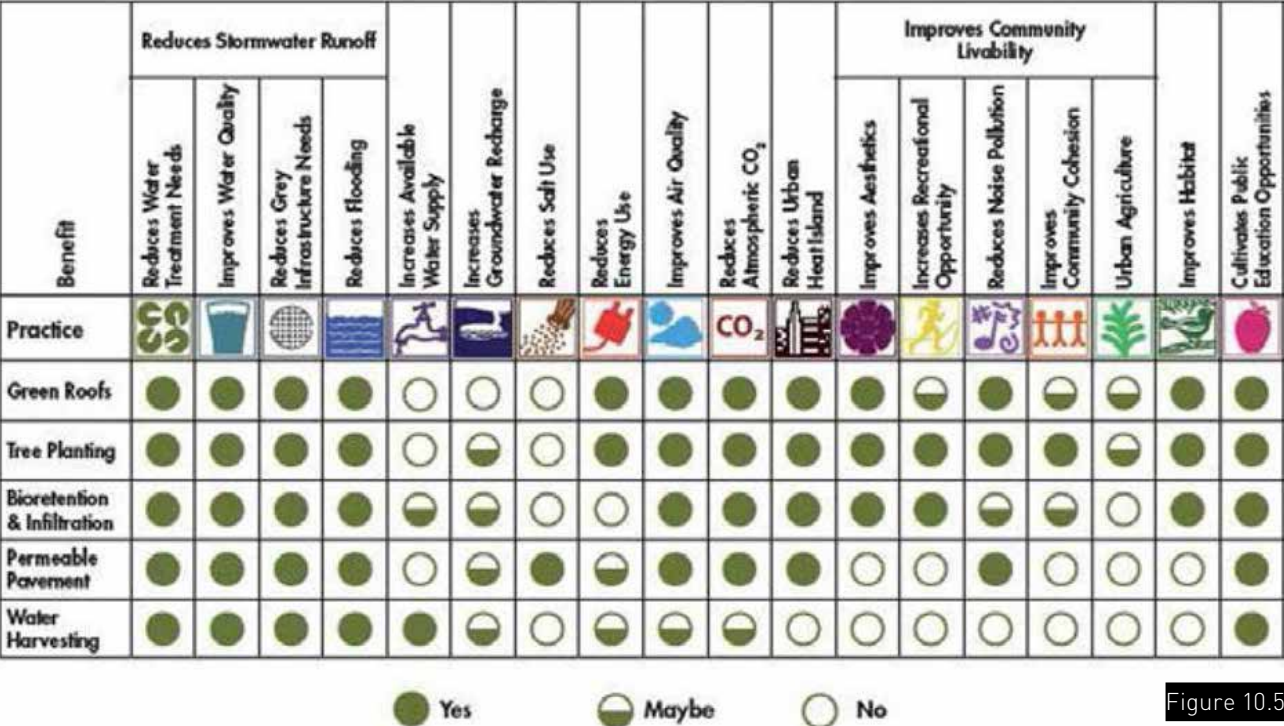


Figure 10.5

The focus of urban stormwater management has changed over the last few decades and it now considers more than just flood mitigation and public health protection aspects. The stormwater industry has developed and adopted new terms to describe these new approaches,<sup>174</sup> including: best management practices (BMPs); green infrastructure (GI); integrated urban water management (IUWM); low impact development (LID); low impact urban design and development (LIUDD); source control; stormwater control measures (SCMs); water sensitive urban design (WSUD); and sustainable urban drainage systems (SUDS).

Most SUDS use the following techniques for the purposes of sustainable water management:

- source control
- permeable paving such as permeable concrete
- stormwater detention and infiltration
- evapo-transpiration (e.g., from a green roof)

- Some examples of SUDS<sup>175</sup> are :
1. permeable pavements (several types)
  2. green roofs
  3. bioretention
  4. sand and organic filters
  5. grassed filter strips
  6. grassed swales (dry) and (wet)
  7. infiltration trench/soakaway
  8. filter drains
  9. infiltration basins
  10. extended detention pond
  11. wet ponds
  12. stormwater wetlands
  13. sediment trap and oil separator
  14. several detailed filtration techniques

Benefits of SUDS

The multiple benefits of SUDS can be shown in several ways. One of them is the Centre for Neighbourhood Technology (CNT) guide for the evaluation of green structure. Using the CNT method (see fig 10.5), the value of a given set of possible investments is expressed monetarily. It gives a clear picture of the multiple benefits of green infrastructure:

Figure 10.5 Multi-values of green infrastructure from the Center for Neighborhood Technology (CNT) guide.<sup>176</sup>



Figure 10.6

- Improves water quality (as discussed)
- Reduces grey infrastructure needs (alternative water sources would otherwise have to be used in dry periods to keep foundations wet to prevent decay)
- Reduces flooding
- Improves air quality
- Reduces atmospheric CO<sub>2</sub>
- Reduces urban heat island
- Improves aesthetics
- Impoves ecology/habitat
- Educational purposes

In the Bryggen case the most important criterion is the amount of water needed to keep the foundations of the buildings and the archaeological deposits wet. Besides minimizing decay, a high removal efficiency of micro-pollutants and a long travel time is advised, which will reduce oxygen, nitrate and sulphate levels that might induce decay of deposits.<sup>178</sup> High removal rates are achieved with SUDS that have several treatment processes - a ‘treatment train’ - where several SUDS are placed one after another. To achieve a high removal efficiency, a treatment consisting only of settlement of particles will not be sufficient.

1. A first treatment step is settlement of large particles in a basin or gross pollutant trap
2. As a second step a rainwater garden is used to store and clean stormwater
3. As a third step a dry swale is added to prolong the travel time (reducing oxygen levels by infiltration to groundwater with long travel times) and the high additional removal rate of pollutants
4. rainwater that falls directly on the surface pavement is encouraged to infiltrate by means of permeable pavement

The treatment train

In figure 10.6 the treatment train of various SUDS at Bryggen is visualized. From the road on the left the water is collected from the stormwater drain; at the inflow a small gross pollutant trap has been added. From the tank the water will flow into the rainwater garden and from there to the swales in the middle of the picture. Permeable pavement and I/T-drainage is used around the area for additional infiltration. The individual kinds of SUDS are discussed in the sections below.

SUDS in the Bryggen area

The selection of SUDS at Bryggen is the result of several workshops in which international examples and infiltration techniques have been discussed. Important criteria that have lead to the final implementation of measures are:<sup>177</sup>

- Space requirements (because this site is a heritage monument, space is limited and should not be altered)
- Minimal intervention in archaeological deposits (no-dig methods are preferred)
- Capability of storing and infiltrating as much water as possible
- Removal efficiency
- Construction cost
- Maintenance effort and cost
- Aesthetics

Figure 10.6 The treatment train and impression of rainwater garden (left) and swales and additional SUDS, such as permeable pavement (middle and right). Photo: F. Boogaard, TAUW.



Figure 10.7:1

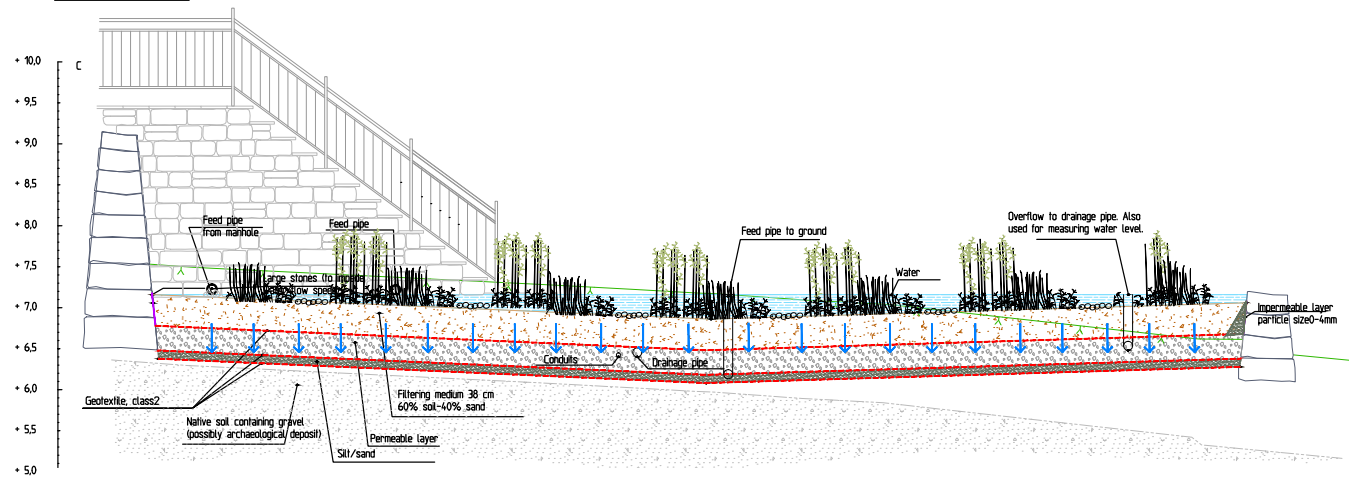
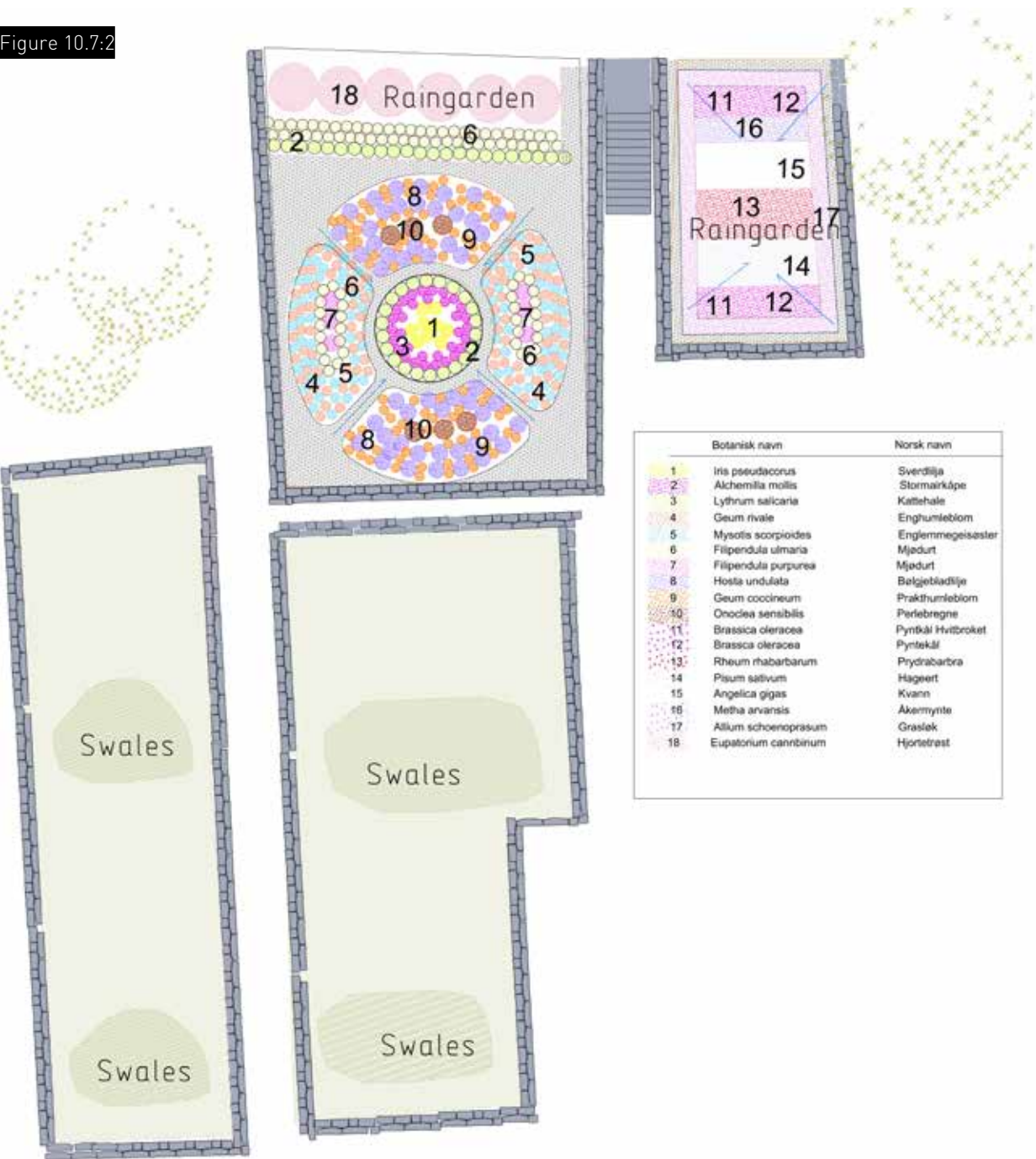


Figure 10.7:2



## RAINWATER GARDEN<sup>179</sup>

Rainwater gardens are sustainable systems where surface water is infiltrated into the ground instead of going down the municipal drains like most runoff does. Basically, a rainwater garden is a shallow, vegetated depression in the ground. A rainwater garden should also be aesthetically pleasing, with flowers and plants that thrive in a wet environment, and the one behind Bryggen boasts a variety of plant species that flower at different times of the year. Below ground there are soil layers that either trap or store rainwater – which comes from numerous sources: the sky, neighbouring roofs, impermeable surfaces, and shallow, interconnected ditches – and then release it slowly into the ground, while at the same time removing any pollutants. A rainwater garden also provides a significant ‘green’ factor in the equation, in that it reduces the load on the municipal drainage systems. It may reduce the risk of local flooding events and, as a result, the city council can be spared the expense of installing larger-capacity drainage pipes and storm drains.

### Rainwater garden in the Bryggen area

The rainwater garden behind Bryggen – the largest of its kind in Norway, and the jewel in the crown of the water-management system – therefore has the following four primary functions:

1. storage
2. infiltration
3. purification and
4. overflow

There are in-built safety valves: overflow features to ensure that excess water from major rainfall events will stream downslope, first to the swales and then to the infiltration ditches in the Bugården zone. The rainwater garden contains 700+ individual herbs and perennials. Whether native or introduced, the selected species are all hardy types that have now become well adapted to Western Norway’s wet climate, and for most of them their historical use – either as ornamental, medicinal, or kitchen plants – can be documented a long way back in time.

The combination of varieties takes into consideration factors such as colour, flowering season, and location with regard to how much moisture they can tolerate. A rainwater garden should comprise many different species, so that the occasional failure of some individual plants or even species will not normally cause any problems.

The rainwater garden is separated into two parts, one on either side of a path leading up to Øvregaten (the medieval High Street). The larger one is an ornamental bed with many classical species drawn from Norwegian horticulture and following traditions associated with the oldest-known Norwegian ornamental gardens. Many of them are not only ornamental plants but also appreciated for their medicinal properties. The smaller garden contains mainly kitchen plants. The section rainwatergarden shows the rainwater garden’s design, with an intake through a narrow upper channel from which water enters the rainwater garden along the whole of the channel’s length. An overflow has been provided to allow excess water to pass through the stone wall lining the garden’s seaward side. The surface’s lowest elevation is in the garden’s geometric centre. This is where it will get wettest, so the plants here are all species that thrive even when inundated for long periods.

### Hydraulic performance and removal efficiency

The hydraulic performance of the rainwater garden depends on many factors. Plants play a significant role regarding the hydraulic conductivity of the filtering media.<sup>180</sup> There is a storage capacity for water of 30 cm on top of the rainwater garden (see fig 10.7). When this height is exceeded the water flows into an overflow and down to the swales. In the case of Bryggen an infiltration capacity around 0.5 m/day can be expected (see next paragraph on swales).

An indication of the removal efficiency of the rainwater garden can be derived from a number of studies. Fig 10.8 (following page) gives an indication of the removal efficiency for several pollutants that can be achieved with filtration, with figures derived from current research.

Figure 10.7:1-2 Cross-section (1) and detailed schematic of rainwater garden (2) in Bryggen. Drawing: Multiconsult AS.



Figure 10.8	TSS		Hydrocarbons		Phosphor		Nitrate		Heavy metals	
	min	max	min	max	min	max	min	max	min	max
Removal efficiency	50	80	50	80	50	60	40	50	50	90



The rainwater garden will be monitored in the coming years and their actual performance with regard to removal efficiency and hydraulic conductivity will be evaluated and compared to the design targets.

## SWALE

Bioretention swales are a SUDS type that has been used for well over two decades globally to provide stormwater conveyance and water quality treatment. Swales are shallow (often < 0.3 m deep), vegetated (generally grass-lined) channels that receive stormwater runoff through gentle side slopes and convey this stormwater downstream by way of longitudinal slopes that are typically inclined at less than 5 % (see Figs. 10.9:1 and 10.9:2). Water quality treatment in a swale occurs through the process of sedimentation, filtration, infiltration and biological and chemical interactions with the soil. Swales have been shown to be very efficient in removing sediment particles from urban runoff.<sup>182</sup>

Swales are relatively simple SUDS devices and they are installed for a variety of reasons including: stormwater transport, water quality improvement, infiltration for groundwater or aquifer recharge, flood mitigation, aesthetics and cost. There are generally two main types of swale:



- 1) grassed or densely vegetated swales with natural soils below;
- 2) swales with filter media or porous soils whose major treatment mechanism is infiltration. The type of swale selected depends on the site's physical parameters (soils, slopes, land use, water-table depth, depth to bedrock), contaminants of concern, and maintenance infrastructure. At Bryggen a simple version of a swale (type 1) has been implemented with no infrastructure underground (this so as not to disturb the underlying archaeological deposits).

### Swales in the Bryggen area

The dry swales just upstream from the Bryggen area are predominately used to increase the groundwater level and humidity in the topsoil cost-effectively to avoid oxygenation and loss of highly organic archaeological deposits in the subsurface. The Bryggen swales consist of two grassed areas positioned side by side. Each swale is approximately 20 m long, 6 m wide and is 30 to 50 cm deep (Fig 10.10). The swales are primarily installed to capture and treat stormwater runoff from upstream roofs and roadway areas and convey most of the water to the groundwater and the underground I/T-system further downstream. Since the primary goal of the swale system at Bryggen is to increase groundwater infiltration for preservation of organic archaeological deposits, particular focus was



placed on efficiency of removal of oxidizing agents such as oxygen and sulphate, which may cause accelerated decay of organic material. The initial hydrological-monitoring results showed that the condition of the archaeological deposits was improved (wet conditions with reduced oxygen levels) by infiltration of stormwater.

### Hydraulic performance and removal efficiency

The hydraulic performance of the swales at Bryggen will be tested in the future. The first tests run before the implementation (with infiltrometer test) showed a minimum infiltration rate of 0.8 m/d, mean value 1 m/d. This has been verified after implementation by visual



inspection: after a rainy day the water depth of about 40 centimetres was infiltrated within half a day (Figs. 10.11:1-2).

With rainfall and evaporation data of Bryggen a first estimation has been made on the hydraulic performance of the swales to determine the design values [see Fig 10.12 following page]. The storage volume has been designed to fit in the available space without altering the aesthetic value of this area: the maximum depth is about 25 cm. The minimum storage is about 12 m<sup>3</sup>, where most of the rain that falls directly on the swale and the rainwater discharged from a connected area of 0.023 ha to the swale will be stored and infiltrated into the ground. A rainfall event of about 35-50 mm/day might well be enough to fill up the entire storage volume of the swale.

Figure 10.8 Indication of pollutant removal in bioretention derived from several studies.<sup>181</sup>

Figure 10.9:1-2 Swales implemented around the world. Swales near roads in Copenhagen (1) and the first swales implemented in the Netherlands in 1998 (2). Photo: F. Boogaard, TAUW.

Figure 10.10 The swales at Bryggen. Photo: A.R.Dunlop, NIKU.

Figure 10.11:1-2 Messrs Rytter, Matthiesen and Boogaard testing permeability of the soil before implementation of the swales (1) and swales filled with water (2). Photo: F. Boogaard, TAUW.



Figure 10.12

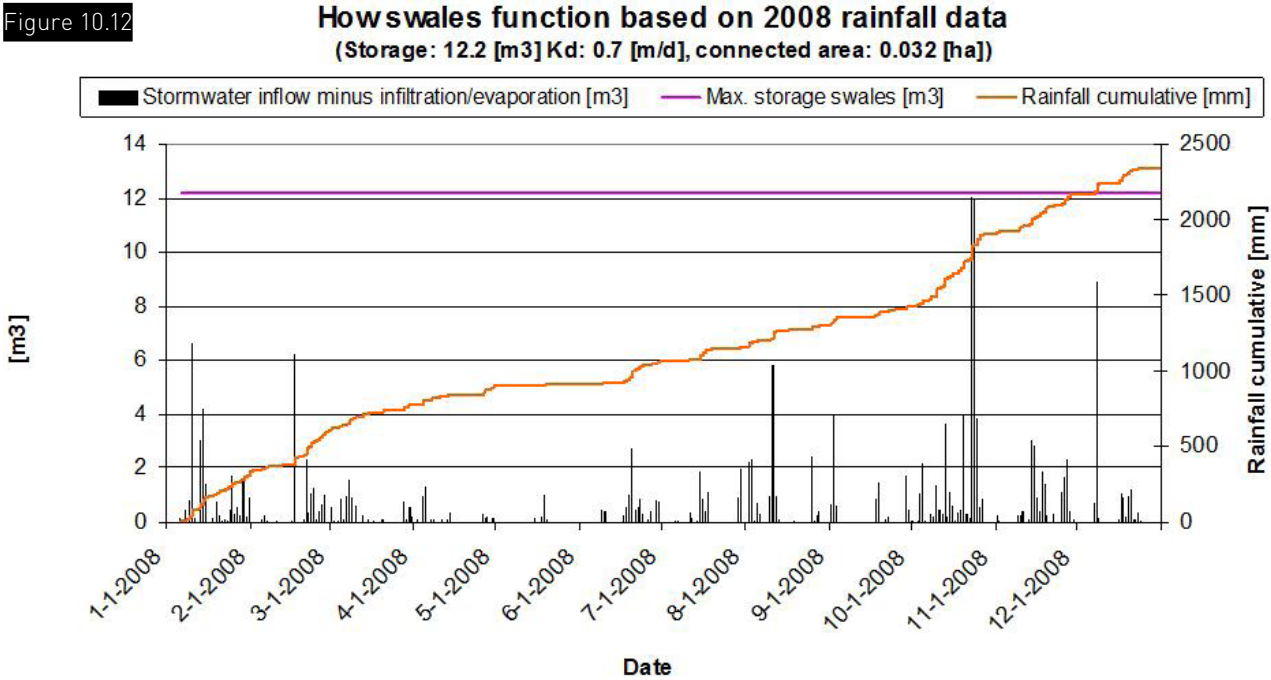


Figure 10.13

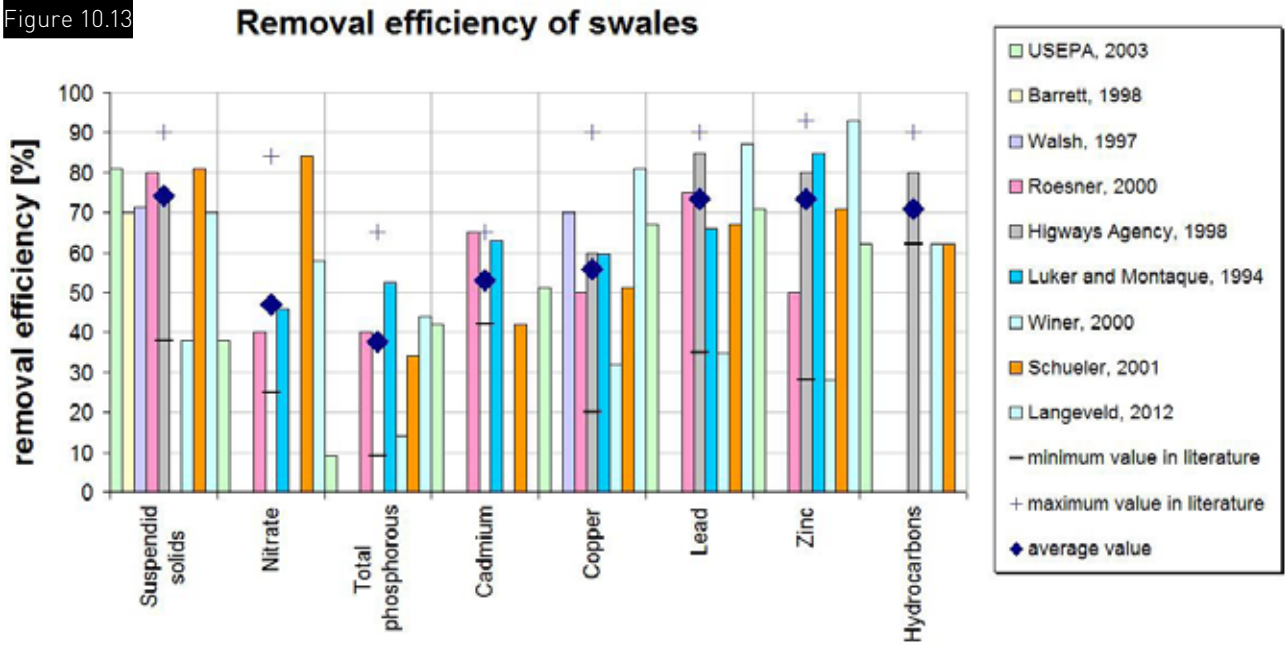
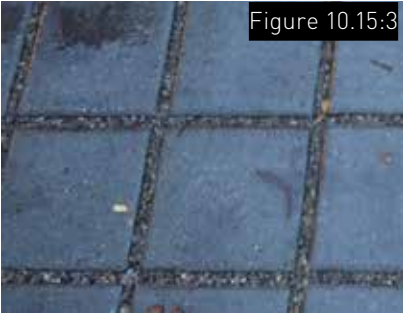
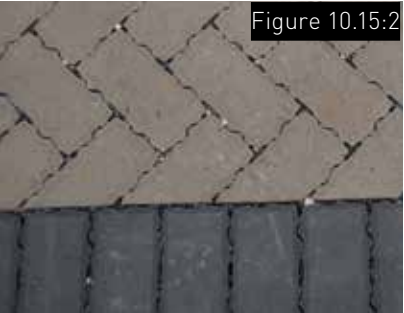
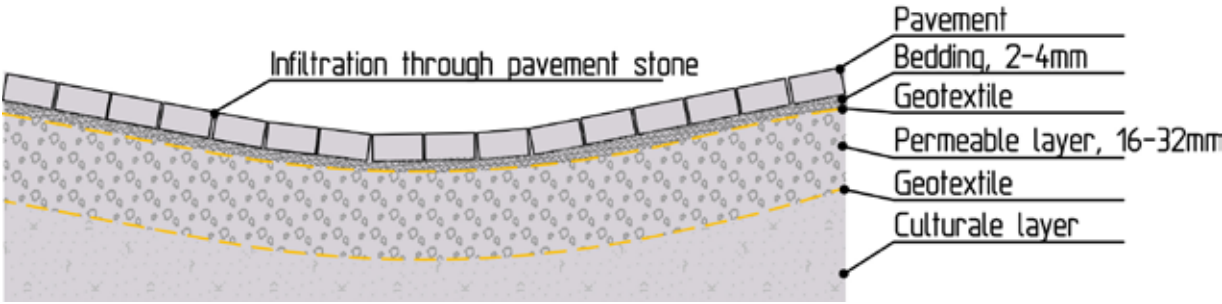


Figure 10.12 Hydraulic performance of the swales to determine the design values.<sup>183</sup>

Figure 10.13 Removal efficiency of swales around the world.<sup>184</sup>

## Typical Permeable Pavement Structure:

Figure 10.14



Micro-pollutants (PAH and heavy metals) accumulate in the swale's topsoil. The removal efficiency of swales is confirmed by several studies world-wide (Fig. 10.13). The efficiency depends on the local situation and dimensions of the swales, but the research gives an indication of the minimum and maximum values that can be expected with topsoil infiltration.

treating and trapping stormwater pollutants. Permeable pavements show an efficiency of removal of suspended solids (depending on construction materials and local conditions) from 60 to 90 %.<sup>185</sup>

## PERMEABLE PAVEMENT

Permeable (or porous) pavements are a type of sustainable urban drainage system (SUDS) treatment device that is used around the world to infiltrate and treat stormwater runoff. Permeable pavements are specifically designed to promote the infiltration of stormwater through the paving and its bedding, where it is filtered through various layers (Fig. 10.14). This can significantly reduce runoff volumes and discharge rates from paved surfaces, potentially minimizing the risk of flooding downstream. Permeable pavements also provide considerable water-quality improvements by

There are several types of permeable pavement typically used in Europe, including concrete pavers with wide joints or apertures, and porous concrete pavers, either with or without wide joints. These are usually manufactured as blocks and are generally referred to as permeable concrete interlocking pavers (PCIP). Concrete and plastic grid pavers (CGP and PGP) are also often used in Europe. The design and function of CGPs and PGPs are similar to PICP; however, the surface area of the individual pavers is generally much larger than those used for PICP systems (Figs. 10.15:1-3). They also have more void spaces to promote infiltration. Stormwater is able to infiltrate through the large gaps in these pavers, which are usually filled with gravel, or topsoil planted with grass.

Figure 10.14 Typical permeable pavement structure. Drawing: Multiconsult AS.

Figure 10.15:1-3 Examples of permeable pavement. Photo: F. Boogaard, TAUW.



TSS		Hydrocarbons		Phosphor		Nitrate total		Heavy metals	
min	max	min	max	min	max	min	max	min	max
60	95	70	90	50	80	65	80	60	95

Figure 10.17

Permeable pavement in the Bryggen area

The pavement just upstream from Bryggen has been made permeable by removing the existing stones and constructing a permeable granulate underneath. The permeable pavement is part of the treatment train. The paths between the swales are left unpaved (gravel) to optimize infiltration (Figs. 10.16:1-2).

Hydraulic performance and removal efficiency

Infiltration rates through newly installed permeable pavement systems have been shown to be very high. However, it is the long-term infiltration performance of a pavement that determines their ultimate success or failure. The Bryggen pavement has not been tested, but the infiltration capacity of newly installed permeable pavement (1 or 2 years) varies in most cases between 100 and 1000 mm/hour.

Fig. 10.17 shows expected removal efficiencies from permeable pavements (figures from various studies). The real efficiency depends on the types of permeable pavement and local conditions. A 60-90 % efficiency of removal of suspended solids can be expected.

Summary of technical data on the treatment train at Bryggen

The design dimensions of the water management system are presented in Fig. 10.18.

CONCLUSIONS

A baseline study was performed to characterize the stormwater quality from the upstream roofs and road areas. Results showed variations in stormwater quality. This may inhibit single-step treatment performance. Therefore, a 'treatment train' of several SUDS measures was developed in order to achieve high pollution-removal rates and to help prevent loss of valuable archaeological deposits and thereby reduce subsidence.

Figure 10.16:1-2 Permeable pavement in Bryggen as part of the treatment train; paths (right) between the swales have been surfaced with gravel to optimize infiltration. Photos: F. Boogaard, TAUW.

Figure 10.17 Expected removal efficiencies of pervious pavements.<sup>186</sup>

Item	Unit	Average value
Maximum area (total watershed w/ roads)	ha	4.3
Rainwater garden		
Width Rainwater garden 1+2	m	9.72 + 5.41
Length Rainwater garden 1+2	m	12.93 + 7.20
Water depth	m	0.3
Gravel layer depth	m	0.5
Expected storage, water and gravel (0.33% water)	m <sup>3</sup>	45 + 50
Estimated infiltration capacity	m/d	
Permeable pavement		
Expected surface	m <sup>2</sup>	150 m <sup>2</sup>
Swales		
Average slope	1:n	1:6
Width total	m	15-20
Maximum depth	m	0.3
Length total	m	15-20
Maximum storage	m <sup>3</sup>	15
Estimated infiltration capacity	m/d	0.8

Figure 10.18

Relevant research stresses the multiple benefits of green infrastructure as: flooding reduction, air quality improvement, aesthetic aspects, ecology/habitat enrichment, and possible educational purposes (a local school may be recruited to carry out maintenance of the rainwater garden at the back of Bryggen).

The use of shallow SUDS to protect and preserve subsurface organic archaeological deposits in a historical urban area with significant legislative limitations for (modern) constructions and deeper excavations is not only cost-effective, but also a robust and practical solution. A monitoring programme will be implemented in the near future to evaluate the effectiveness of the treatment train with regard to protecting the archaeological deposits. This is expected to produce more valuable results. At some future date, phase 2 will be implemented, where in the area upstream from the areas with SUDS more green infrastructure will be implemented to stimulate infiltration of rainwater.

Figure 10.18 Design dimensions of the water management system. Table: F. Boogaard, TAUW.





# 11

## SUBSIDENCE AT THE BRYGGEN SITE

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Jann Atle Jensen  
Multiconsult AS

The ground surface at the World Heritage Site Bryggen in Bergen is at an elevation of about 0.9 m asl along the seaward facade, and at about 5.0 m asl at its highest along Øvregaten. From a geotechnical perspective, the ground beneath Bryggen consists of a top layer of wooden foundations and a layer of non-compacted fill (archaeological deposits) with a high content of organic matter. The thickness of the latter layer varies between 2 and 10 m. The fill is deposited on top of the seabed deposits and beach deposits of silt, sand and gravel.

The seabed deposits are soft and may contain some humus. The thickness of these deposits is 1-2 m. They rest on top of compact layers of sand, gravel and moraine. The depth to bedrock from the surface of these compact layers varies from 6 to 16 m.

## SUBSIDENCE RATES AND MONITORING

### How does subsidence in soil occur?

General subsidence in the traditional, geotechnical sense follows the compression of cavities (pores) in soil, after the emission/migration of pore water and gases. The compression is due to the effective load of the soil volume itself, or due to external load being applied to the soil volume.

Subsidence in organic, subsidence-sensitive soils, such as the archaeological deposits at Bryggen, normally happens due to one or more of the following factors:

I) Momentary (elastic) and primary subsidence (elasto-plastic subsidence):

- Load increase on the ground by fills, construction of buildings, and large, long-term loads in storehouses. This has happened/been going on many times in many different locations at Bryggen after the 1702 fire.
- Lowering of the groundwater level (hydraulic head) leading to increased effective tension in layers sensitive to subsidence. This happened when the hotel to the northwest of the World Heritage Site was built in 1979-80. The construction activity led to a permanent lowering of the groundwater level under and around the hotel, and also in the subsidence-sensitive archaeological deposits in the vicinity of the hotel's construction pit.

This category of subsidence decreases significantly after some months, and can last up to a few years.

II) Creep subsidence and other secondary subsidence (plastic subsidence and decay)

- Transformation and resettling of mineral and organic soil grains.
- Decay of organic matter, which forms cavities (pores) and weakens soil structures, which in turn leads to increased compaction by the dead weight of the soil volume and other loads.

Also, drying and swelling processes can occur that cause volume alterations in humic soils and wooden elements. Variations of the water table, particularly seasonal, can cause a cyclical process of elastic uplift and sinking of the ground. Such processes can influence the measurements over short intervals of time, but in long-term measurement series the effects will be evened out. It is therefore important that, in humic soils, subsidence measurements and monitoring be conducted over a sufficiently long period of time.

### Primary and secondary structural damage caused by subsidence

Differential subsidence alongside a building will eventually lead to obliquities and fissures in the construction. The amount of damage this will cause depends on the degree of relative skewness in subsidence and the induced deviation from level, or vertical, which can be observed in the building. It will naturally also depend on the type of building, its geometry, the type of building materials in the construction, etc. For example, a wooden building will normally withstand a greater amount of subsidence (and relative obliquity) than a brick building before substantial structural damage occurs.

Subsidence can also damage the ground and infrastructure in the ground, such as pipes, ducts, cables, drainage, etc.

As a consequence of damage to buildings and ruptures in drainage, pipes, etc., secondary damage due to water penetration can occur. This could be damage due to humification of construction materials, or to rot, fungus or frost. Such damage acts to break down the construction over time.

### Objectives and methods.

The measurement of subsidence consists of two main categories, as described below: Surveying of fixed points on/in the ground in the period 2000-14; designated 'S'-points. The measurement points are at the top of so-called 'soil spears' - thin, ca. 0.5-m-long aluminium-pipes rammed into the ground to their full length. New points have been established during the whole monitoring period. Some have been lost because of ongoing construction works.

Surveying of fixed points on wooden buildings ('French wood-screws') and stone buildings in the period 1999-2014; designated 'T-points'.

The reference level for all measurements is a fixed point (F1) in solid bedrock in the eastern part of the Bryggen area, with known elevation (datum Norwegian Normal 1954).

Since 2000, the measurements have been conducted by the same person and the same levelling equipment (ANKO AS) to make the source of error attached to method and equipment as small as possible.<sup>187</sup>





Figure 11.1

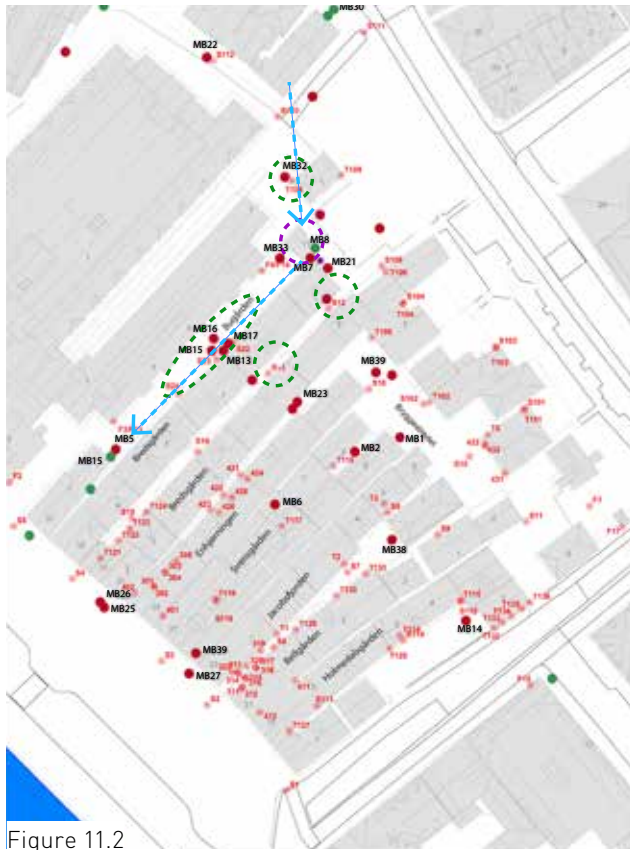


Figure 11.2

## MONITORING RESULTS - SITUATION BEFORE AND AFTER MITIGATION

We have assessed subsidence rates before and after mitigation in four areas at or near the sheet pile wall, as shown in Fig. 11.1 and 11.2 (measurement points S12, S13, S22-S24 and T108) to demonstrate the effect of the mitigation.

In the period from October 2000 to June 2011, in point S12 one has observed a total subsidence of 20.5 mm obtained through a fairly constant subsidence rate of 1.9 mm/year. This has been the case until groundwater mitigation

Figure 11.1 Locations of monitoring wells mentioned below are marked by yellow stippled circles.  
Map: Multiconsult AS.

Figure 11.2 Green stippled ellipse and circles show the subsidence measurement points mentioned below. Lilac circle marks the division between the upper and lower parts of the I/T-system. Blue arrows show roughly the location of the I/T-ditch and the direction of infiltration water running in the pipe. The I/T-ditch runs not far from the surface along the outside of the sheet piling.  
Map: Multiconsult AS.



Figure 11.4:1



Figure 11.5:1

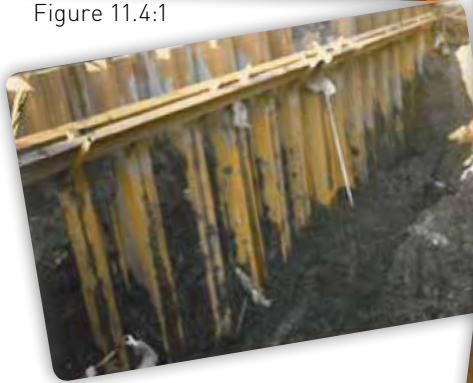


Figure 11.4:2



Figure 11.5:2



Figure 11.3:1



Figure 11.4:3



Figure 11.3:2



Figure 11.5:3

Figure 11.5:1-3 Shows sub-grade blasted bedrock below sheet piling at Schøtstuene. Fig.11.5:2 in-situ bedrock before blasting at «Meyers Steinkjeller» (point T108) and signs of water penetration through the wall. Fig.11.5:3 (bottom) shows filled and compacted bottom of excavation area. Fill consists of permeable crushed stone.  
Photo: Noteby AS.

Figure 11.3:1-2 Sheet piling alongside Bugården/Bredsgården. Transition to sub-grade blasted bedrock is below wooden building (by the point S107 at «Bugårdens ildhus», transition between upper and lower part of the I/T-system). The white building is «Meyers Steinkjeller» and the red buildings belong to the Schøtstuene complex.  
Photo: Noteby AS.

Figure 11.4:1-3 Archaeological deposits (disturbed) and wooden foundations over deposits of sand and gravel (seabed layers) during excavation for sheet piling installation in 1979. The groundwater level had then been artificially lowered by pumping inside the excavation area.  
Photo: Noteby AS.

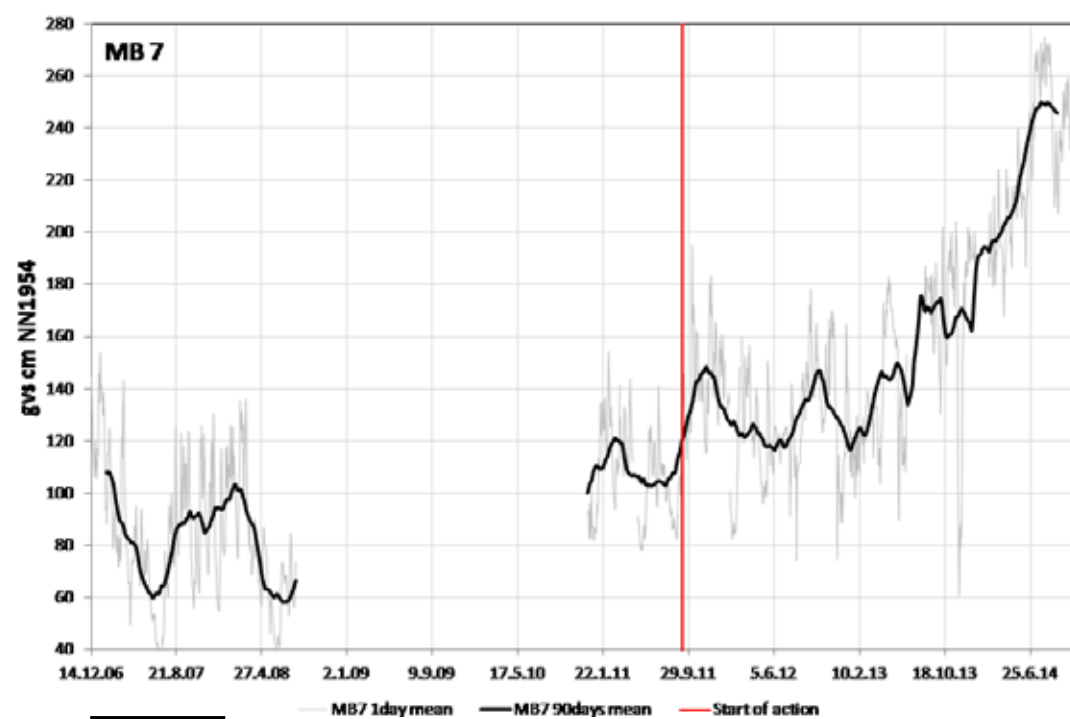


Figure 11.6:1

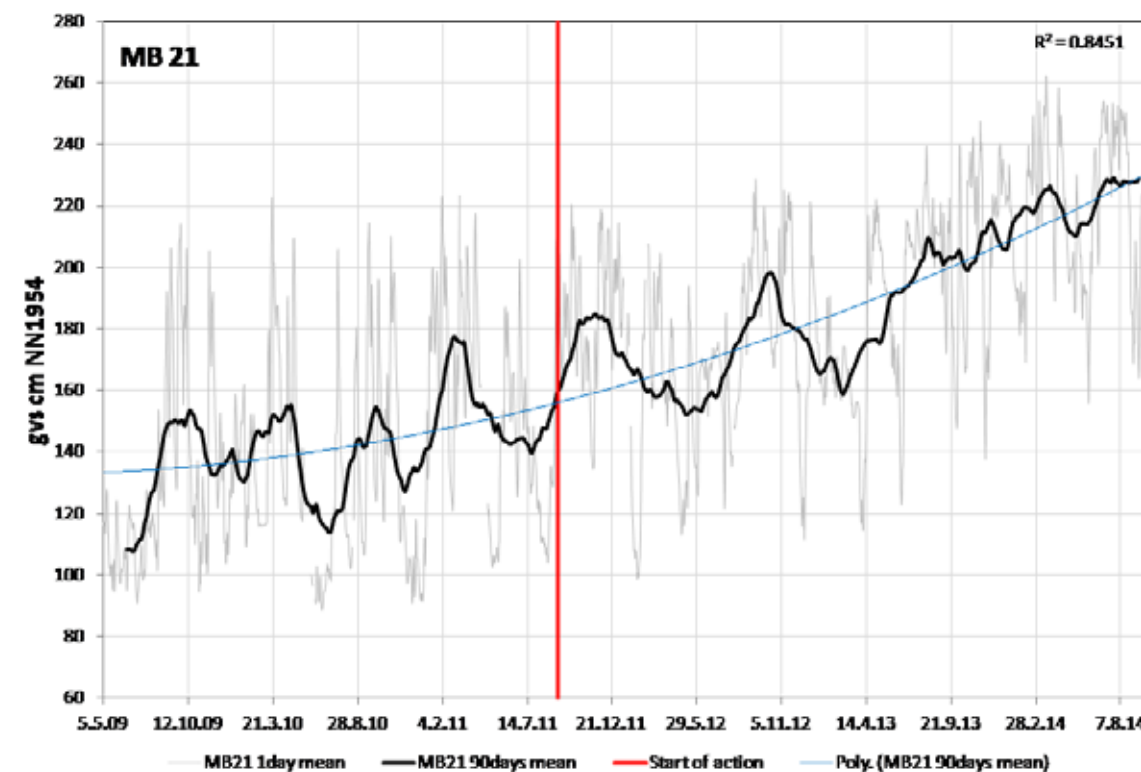


Figure 11.6:2

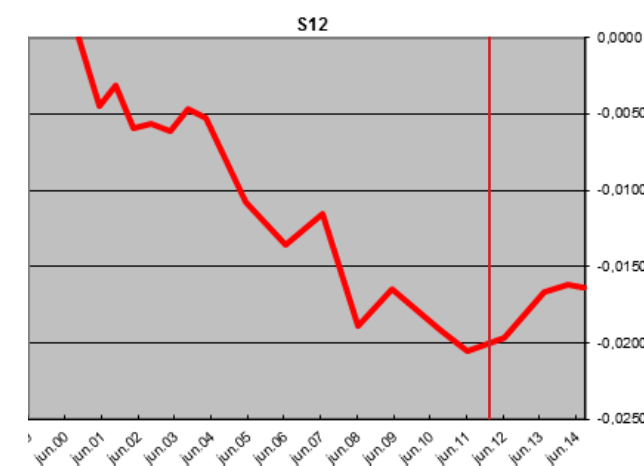


Figure 11.6:3

measures through infiltration were implemented nearby and downstream of monitoring wells MB7/ MB21, situated close to measurement point S12. The start-up time for water infiltration in the lower section of the I/T-system (from the manhole close to point S107 and downstream) is shown with a vertical, red line in Fig.11.6. Minor measures, like raising the groundwater

level by a few decimetres inside the sheet piling, had been undertaken earlier, from the autumn of 2010. The effect of these measures can be seen from the water-level measurements in MB21. From June 2014, water has also been supplied to the rain gardens and swales in the Bryggen park area, upstream of Bredsgården, to increase the groundwater supply.

In the period from June 2011 to August 2014, as is shown by the water-level measurements, the average level in MB21 has been raised by ca. 0.65 m: from ca. 1.55 m asl to ca. 2.2 m asl (ground surface at 4.1 m asl); and in

Figure 11.6:1-3 Development of subsidence at point S12 and water levels in monitoring wells MB7 and MB21 at the back of Bredsgården/Bugården. Measurement points and wells are all situated more than 10 m away from the sheet pile wall. Multiconsult AS.<sup>188</sup>

MB7 the increase was ca. 1.30 m: from ca. 1.20 m asl to ca. 2.50 m asl (ground surface at 4.2 m asl). In the same period, the subsidence at the nearby point S12 has stopped and been reversed to uplift. The point has had an uplift of 4.1 mm in the period. The uplift is most likely an elastic response to the raising of the groundwater level, and this trend will not continue. The overall aim of the project is to reduce the subsidence rate to 1.0 mm/year or less, and this has probably been achieved at this point. We see here a significant connection between the raising of the groundwater level and the reduction of subsidence at nearby measurement points.



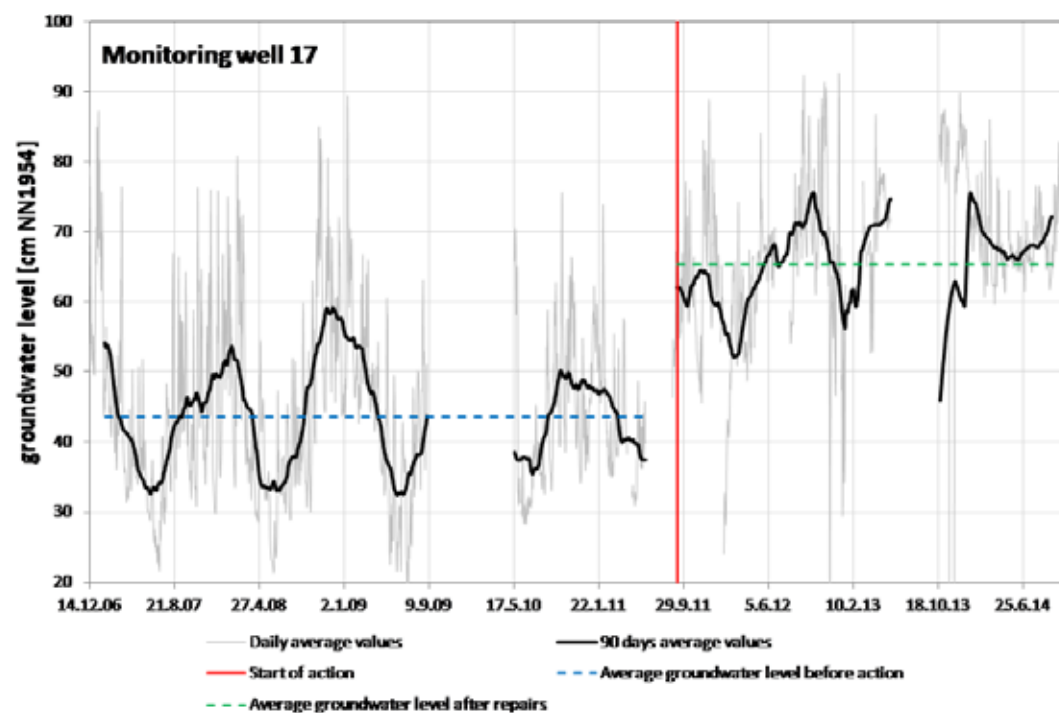


Figure 11.7:1

In the period from October 2000 to June 2011, a total subsidence of 45.3 mm has been observed at point S13, obtained through a fairly constant subsidence rate of 4.1 mm/year. This has been the case until groundwater mitigation measures through infiltration were implemented nearby and downstream of monitoring wells MB15/MB17, situated close to measurement point S13. The start-up time for water infiltration in the lower

Figure 11.7:1-3 Development of subsidence at point S13 in Bredsgården and water levels in monitoring wells MB15 and MB17 in Bugården, parallel to S13 in the Bredsgården passageway. Point S13 is situated about 10 m away from the sheet piling, while the wells are situated close to the pile wall. The groundwater situation at S13 thus is probably more favourable to preservation than in the vicinity of the two wells, since the groundwater level here is probably closer to the surface. Multiconsult AS.<sup>189</sup>

section of the I/T-system (from the manhole close to point S107 and downstream) is shown with a vertical, red line in Fig. 11.7. Minor measures, like raising the groundwater level by a few decimetres inside the sheet piling, and point-by-point sealing of the top of the pile wall, had been undertaken earlier, from the autumn of 2010.

In the period from June 2011 to August 2014, as shown by the water-level measurements, the average level in MB15 has risen by ca. 0.45 m: from ca. 0.45 m asl to ca. 0.90 m asl (surface at 2.1 m asl); and in MB17 the increase was ca. 0.20 m: from ca. 0.45 m asl to ca. 0.65 m asl (surface at 2.1 m asl). In the same period, the subsidence at the nearby point S13 has been considerably reduced. This is one of the points that have had the greatest amount of

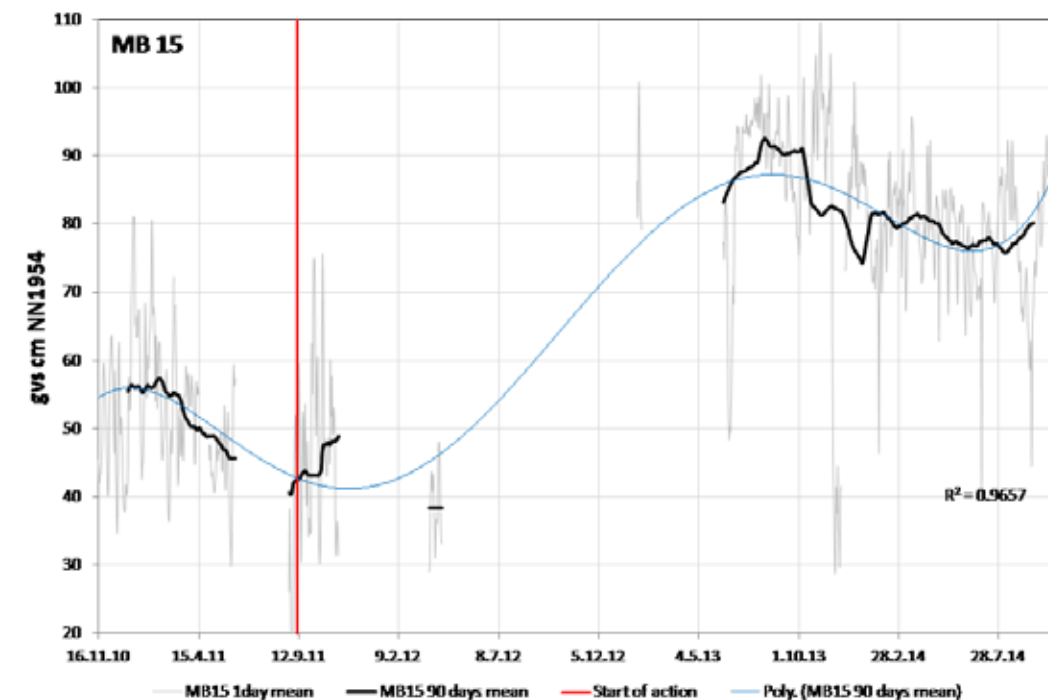


Figure 11.7:2

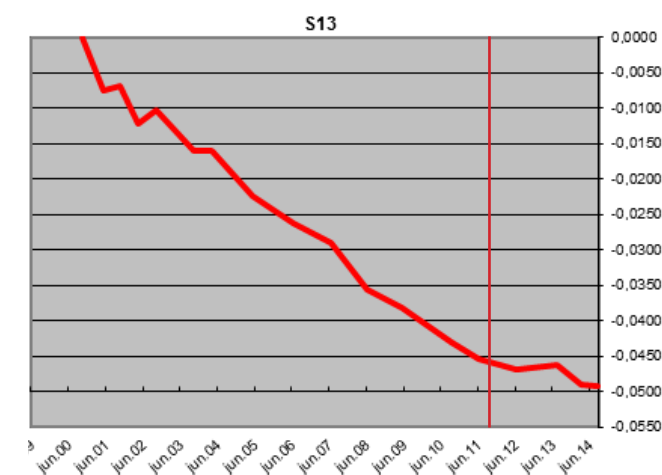


Figure 11.7:3

subsidence in all of Bryggen before the implementation of groundwater measures. After the implementation of such measures (June 2011 to August 2014), it has had a total subsidence of 3.8 mm, which equals a subsidence rate of 1.27 mm/year. The aim of the project is to reduce the subsidence rate to 1.0 mm/year or less, and this has nearly been achieved in this point. The groundwater level at this point, S13, is probably closer to the surface than it is in the two monitoring wells lying close to the sheet piling. Thus, the aim of a groundwater level ca. 1.0 m below surface could be nearly achieved here.

At this point too, we see a significant connection between the raising of the groundwater level and the reduction of subsidence at nearby measurement points.

In the period from October 2000 to June 2011, at points S22, S23 and S24, which are also located nearby the

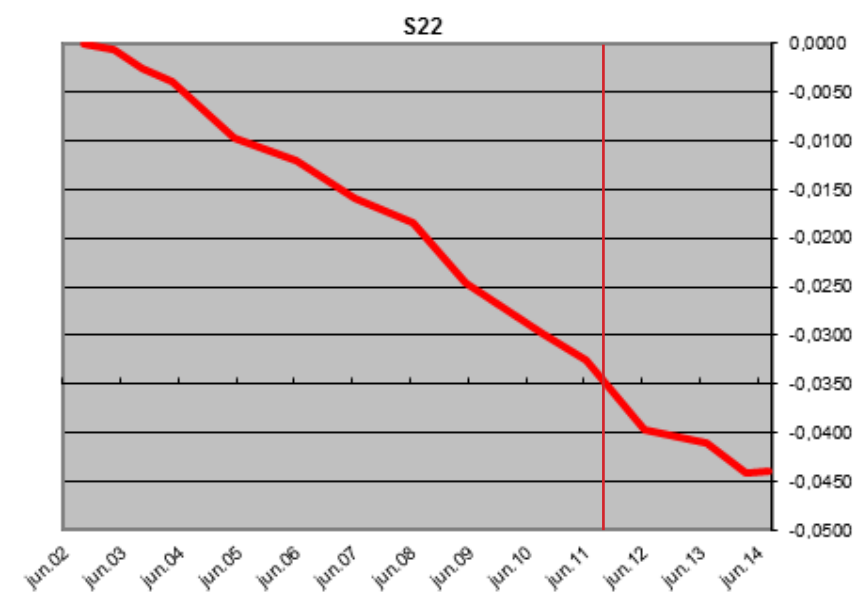


Figure 11.8:1

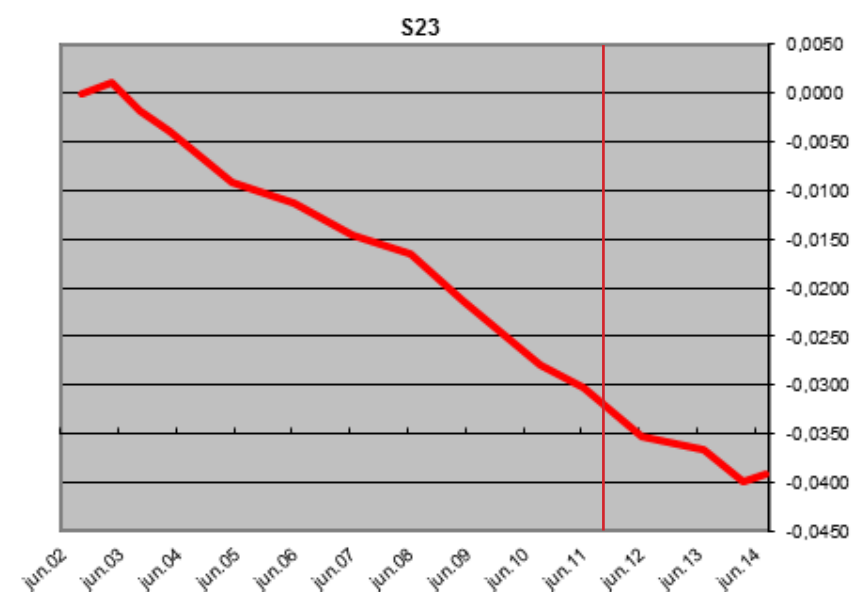


Figure 11.8:2

monitoring wells MB15 and MB17, one has observed a total subsidence of 32.3 mm, 30.3 mm and 17.3 mm respectively, obtained through fairly constant subsidence rates of 3.6 mm/year, 3.4 mm/year and 1.9 mm/year respectively. This has been the case until considerable groundwater mitigation measures through infiltration were implemented nearby and upstream and downstream of the three measurement points. The start-up time for water infiltration is shown with a vertical, red line in Fig. 11.8.

Figure 11.8:1-3 Development of subsidence at points S22, S23 and S24 in Bugården close to and below monitoring wells MB15 and MB17 in Bugården, parallel to S13 in the Bredsgården passageway. Both the wells and the measurement points are situated right outside the sheet piling. Multiconsult AS.<sup>190</sup>

After start-up of water infiltration in the lower section of the I/T-system (infiltrating from the manhole close to point S107 and downstream), in the period from June 2011 to August 2014, the subsidence at the three points S22, S23 and S24 has been measured to be 11.4 mm [3.8 mm/year], 8.9 mm [2.9 mm/year] and 8.7 mm [2.9 mm/year] respectively, a development equivalent to what it was before mitigation measures. But if one focuses on the later part of the period, from June 2012 to August 2014, the result is somewhat different. Then the points S22, S23 and S24 show a subsidence of 4.2 mm [2.0 mm/year], 4.0 mm [1.9 mm/year] and 3.4 mm [1.6 mm/year] respectively.

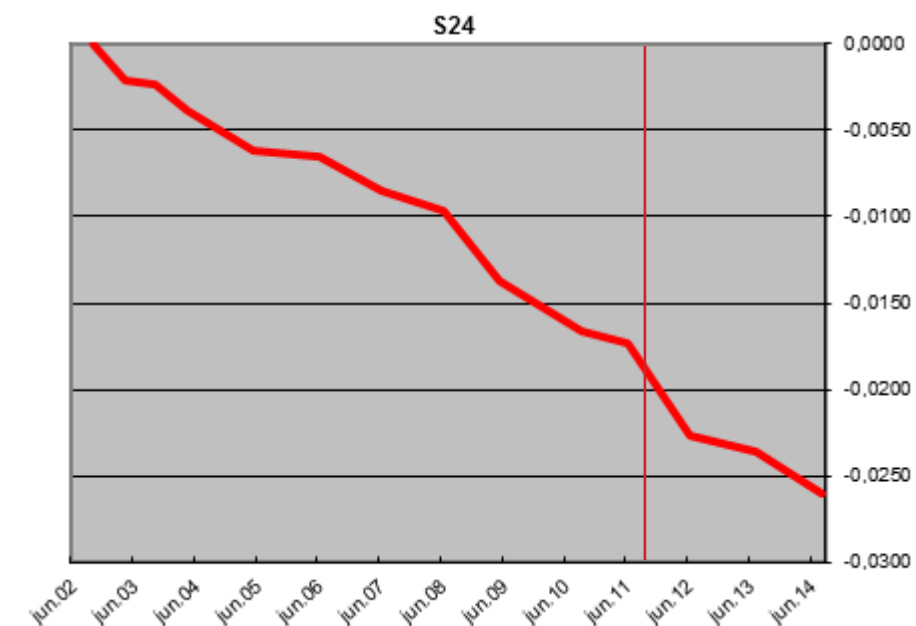


Figure 11.8:3

The aim of the project is to reduce the subsidence rate to 1.0 mm/year or less, and this has partly been achieved in these points by the fact that the subsidence rate has been clearly reduced during the past two years. But a complete goal achievement will also require the groundwater level to be raised further, and/or the pore pressure in deeper layers to increase considerably more than what has been achieved below the subsidence measurement points here, which incidentally are located very close to the sheet piling.

In sum, these points also show a significant connection between the raising of groundwater level and the reduction of subsidence at nearby measurement points. For the aim to be achieved completely, however, the groundwater level must be raised further, and/or the groundwater pressure

in deeper layers (soil and bedrock) must be increased. The latter applies to layers where the groundwater pressure is lower than the hydraulic head calculated from measured top groundwater level.

In the period from September 2010 to July 2013, in point T108, one has observed total subsidence of 3.5 mm, giving a subsidence rate of 1.2 mm/year. This point is located by the lower part of the upper section of the I/T-system, which has been supplied with water since the spring of 2014. Simultaneously, water has been fed to the rainwater gardens upstream of this area since June 2014.



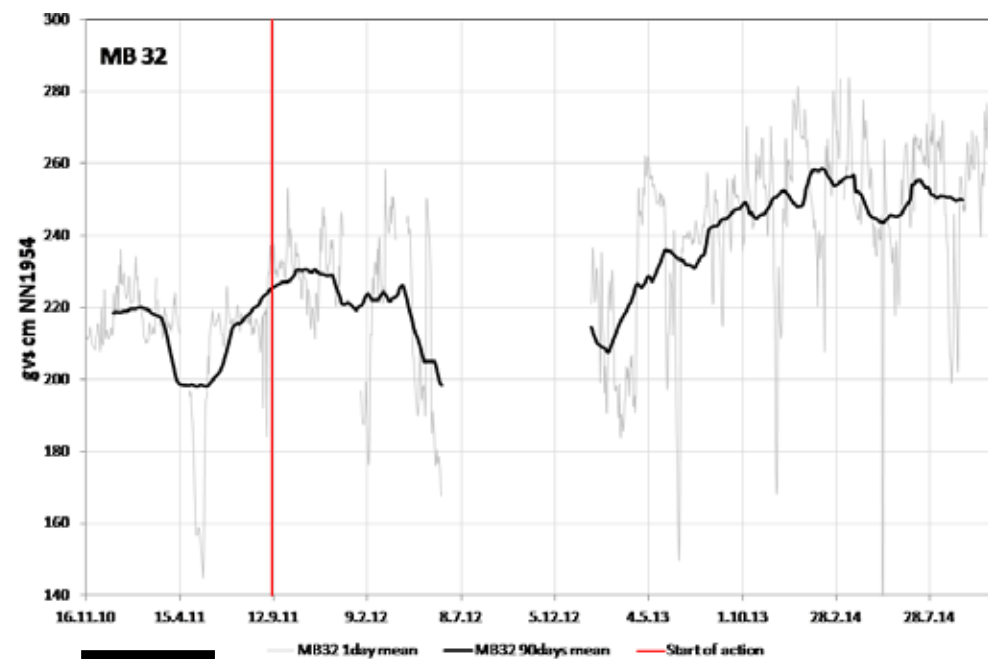


Figure 11.9:1

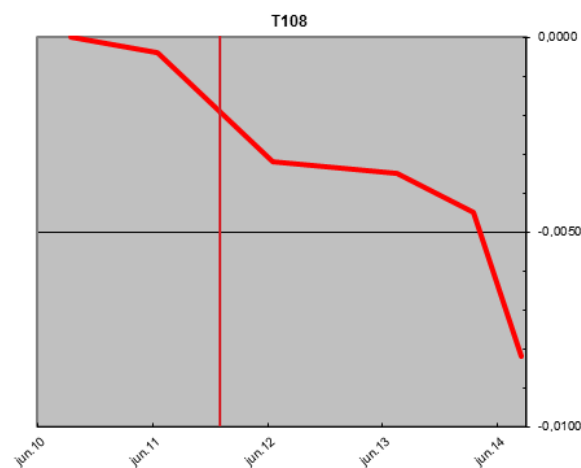


Figure 11.9:2

In the period from the autumn of 2010 to the autumn of 2014, the water level in MB32 has been raised by 0.4 m: from 2.2 m asl to 2.6 m asl (ground surface at 4.4 m asl). From the autumn of 2011 water has been supplied to the lower section of the I/T-system (from manhole close to point S107 and downstream). The manhole, which separates the upper and lower sections of the I/T-system, is situated just downstream of T108. The start-up times for water supply to the lower and upper sections of the

Figure 11.9:1-2 Development of subsidence at point T108 in the building «Meyers steinkjeller» and water levels in monitoring well MB32 nearby. Both the well and the measurement point are situated right outside the sheet piling in the lower part of the upper section of the I/T-system. Multiconsult AS.<sup>191</sup>

I/T-system are shown with a red, vertical line and a green, stippled vertical line respectively in Fig. 11.9.

In the period from July 2013 to August 2014, in T108, one has observed a total subsidence of 4.7 mm, giving a subsidence rate of 4.3 mm/year. The larger part of the subsidence took place during the dry and warm summer of 2014, between the measurement rounds in March and August. In the preceding eight months, the subsidence was only 1.0 mm, giving a subsidence rate of 1.5 mm/year, which is consistent with subsidence rates of the preceding years. The substantial subsidence during this dry summer could partly be caused by ongoing drying and swelling processes in organic matter (peat, humus and wooden components) in the upper layers in the unsaturated zone above the groundwater level, which can cause certain volume oscillations throughout the year.

This point differs from the rest in that the subsidence rate increases considerably in a dry period, even when water is being infiltrated, and the groundwater level (water table in soil) here has been raised, and comprehensive sealing measures have been undertaken along the top of the sheet piling to prevent loss of water along the I/T-ditch. A significant difference between the upper and lower infiltration sections is that the pile wall in the lower section was hammered down to relatively impermeable moraine below poorly permeable humic archaeological deposits, whereas the wall in the upper section was hammered down into the bedrock, which was subsequently uncovered and sub-grade blasted and then covered over with permeable blasted and crushed rock. Along the bottom of the wall there is a substantial leakage of water, as well as through the fractured bedrock underneath the wall's foot. In addition to this comes the direct leakage through the deeper parts of the wall, which is probably also present along the lower section of the I/T-system.

It appears very likely that the leakage through bedrock and layers of sand and gravel along the foot of the wall and beneath it is so massive that the present pore pressure in bedrock and soils is significantly lower than the full hydraulic head that could theoretically be attained. The archaeological deposits lying on top of fractured bedrock and sand and gravel are much less permeable than the last-mentioned. When the influx of groundwater from the area upstream of Bryggen is reduced, in this case due to a warm and dry summer, the pore pressure will continue to fall in bedrock, sand and gravel and in the deeper parts of the archaeological deposits, even though water is being infiltrated into the uppermost layers. Perched groundwater can occur periodically in the archaeological deposits. If subsidence trends are to be reduced in accordance with the aims of the project, the groundwater level must be raised further and/or the groundwater pressure in deeper layers (soil and bedrock) must be raised. The latter applies to layers where the groundwater pressure is lower than the hydraulic head calculated from measured top groundwater level.

To maintain the water table at today's level it is necessary to supply relatively large volumes of freshwater to the I/T-system and the rainwater gardens. This water comes from several sources, such as surface water, municipal drinking water, and recirculation of water from inside the pile wall. The large leakage rate through and underneath the pile wall also involves a risk of increasing erosion of fine-grained fill from the bottom of the pile wall, and the whole process will spiral. Furthermore, as the pile wall itself corrodes, the amount of leakage through it is likely to increase.

## Further reduction of the subsidence rate

To reduce further subsidence, it is necessary to raise the groundwater level and if possible increase the pore pressure in the deeper layers. As it is very difficult to increase the infiltration volumes, one must either:

- Seal the pile wall and the foot of the wall permanently and grout the bedrock in areas where there are leakages. This will improve the groundwater conditions and even further reduce the development of subsidence, reduce the need for drinking water and pumping of water to the infiltration system, reduce the risk of groundwater erosion and corrosion of the pile wall and give a more sustainable solution altogether.
- Establish a network of deep infiltration wells to supply infiltration water to deeper layers as a supplement to the shallow infiltration taking place today. This measure will probably reduce the development of subsidence, but will lead to intervention in archaeological deposits and the need for even more infiltration water. It will also increase the corrosion rate of the steel piles as well as the risk of deep erosion.

Both measures will involve substantial costs.

In areas where the water table has been raised, both inside and outside the sheet piling, and in the areas where one wants to raise it in the near future, it is important to reduce the leakages through and underneath the wall. Leakages could increase as a result of a larger flux rate through and underneath the wall and the possible subsequent increased erosion of fill. The most important measure to be done quickly, and without unreasonable cost, is to reduce the corrosion rate of the pile wall. This can be achieved by electrochemical methods such as implementing cathodic protection of the wall or supplying it with galvanic anodes. Secondly, one should consider grouting the fissured bedrock beneath the wall, as well as the contact line along the bottom of the wall.

Future subsidence monitoring

Monitoring of subsidence trends at Bryggen is recommended as follows:

- From June 2015 annual subsidence measurements and deformation measurements on all measurement points at Bryggen, Schøtstuene, and the Hanseatic Museum at the southern end of Bryggen, with evaluations every second year.

Measurement points that have been removed due to works in the area are re-established in the same points and are re-included into the schedule from 2015 on.

- One should consider establishing a satellite monitoring programme for Bergen for monitoring of vertical deformations, where Bryggen is included. This could be a good supplement to the subsidence measurement schedule, and could uncover unknown and new threats to the World Heritage Site, particularly related to the planning and carrying out of large projects upstream of Bryggen (projects that influence the groundwater level), and map at best at an early stage the need for any mitigation measures.

CONCLUSIONS AND RECOMMENDATIONS

The efforts to raise groundwater levels have proven successful in that over a large area one has achieved a raised groundwater level and a significant reduction of the subsidence rates in the protected archaeological deposits. This will lead to a reduction of subsidence damages and secondary damages to the protected buildings of the World Heritage Site in the future. The method of shallow infiltration of suitable fresh water therefore has a large potential of transferral to other archaeological sites with more or less similar problems.

Because of special local conditions relating to a leaky and sub-grade blasted sheet pile wall with many leakage points, the groundwater-level target not been achieved throughout the entire World Heritage Site area. If this is to happen, additional measures must be undertaken.

It is recommended that the monitoring of subsidence and the automatic monitoring of groundwater levels at Bryggen be continued from 2015 and onwards, but not as intensely as it is today.

If one wishes to achieve a further reduction of the subsidence rates, thereby also reducing future damage to the World Heritage Site, such as decay of archaeological deposits and subsidence damage with secondary damage to buildings and infrastructure, further groundwater mitigation measures (outlined elsewhere in this chapter must be carried out.





# 12

## MAINTENANCE AND MONITORING

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Hans de Beer, Floris Boogaard, Jann Atle Jensen & Henning Mathiessen

INTRODUCTION

The water management system that has been established at Bryggen will need to perform in many years to come, and the effects of the mitigation measures need to be documented for future evaluation and risk assessments for the management of the cultural heritage site.

The operational performance of all elements in the water management system as described in chapters 8 to 10 requires regular maintenance and control to avoid deterioration and malfunction of the system by e.g. clogging, contamination, power failure, mechanical disruptions or other negligence or maltreatment of the system. Performance monitoring is directed towards timely identification and warning of possible disruptions, and as such ensure that repairs or maintenance work can be carried out accordingly. In this chapter, we will describe the regular maintenance and performance monitoring program for the complete water management system.

The effects of the mitigation measures on the preservation of the site will need to be documented for future evaluation and risk assessment. In this book, several methods have been described to measure and evaluate indicator parameters that give information on the preservation conditions in the archaeological deposits (a.o. oxygen concentration, redox potential, soil moisture, groundwater level), as well as on the stability of the site (subsidence rate). In this chapter, we will summarize the monitoring measures that document the effects of the mitigation, and describe how we envisage the future monitoring programme of the World Heritage Site. Maintenance and monitoring of the water management system

MAINTENANCE OF THE WATER MANAGEMENT SYSTEM

The monitoring and evaluation of SUDS in different European countries have yielded a wealth of experience which allows us to review and expand our guidelines for maintenance of SUDS to guarantee their performance in time.

Some of these general guidelines are directly applicable to the implemented treatment train at Bryggen, containing of raingarden, dry swales, permeable pavement and subsurface infiltration- transport (I/T)- systems. With respect to maintenance of the treatment train the following general guidelines are important:

Element	Surficial infiltration swales and raingarden	Subsurface infiltration I/T-system	Permeable pavement
Topsoil layer	x		
Infiltration pipe (perforated)		x	
Infiltration well (vertical)		x	
Infiltration points (downspouts)	x	x	
Infiltration trench (along sheet pile wall)	x	x	
Permeable pavement (cobblestones)			x
Permeable pavement (gravel path)			x
Groundwater drain (level control)	x	x	x
Rainwater sewer (overflow)	x	x	x
Open street gutter	x		x
Slot drain	x		
Gully		x	
Geo-textile	x	x	
Control unit	x	x	
Overflow points	x	x	x
Silt-sand trap/filter	x	x	x

Figure 12.1

1. SUDS should be accessible at all times for maintenance;
2. Proper use and long-term life of SUDS needs adequate communication between the developers, spatial planners, consultants, architects, engineers and inhabitants;
3. Continuously available proper exceedance pathways reduce the risk of erosion, improve the removal efficiency and minimize the land use;
4. Filters are required to prevent inflow of coarse particles and material (twigs, leaves etc) into the system;
5. Controls provide opportunities to regulate and adjust the system after construction (weir heights, infiltration level control etc);
6. A maintenance guidebook is essential for knowledge sharing and long-term functioning of SUDS;
7. Frequent inspection of the system and sharing knowledge is beneficial to the growth of knowledge and experience.

Practical maintenance efforts depend on the elements/ objects and specific detailing of the SUDS. The choice of mitigation measures at Bryggen has been based on uncomplicated low-maintenance requirements for the individual system elements in the water management system. These elements play a major part in the management and maintenance of the system.

SUDS can function well as long as design and maintenance is in accordance with the general guidelines. Research on SUDS has shown that after years of monitoring no significant loss of infiltration capacity has been found when using general guidelines for design, construction and maintenance. Common failures in the design, construction and maintenance of SUDS are gathered from several locations and translated to recommendations for maintenance efforts at Bryggen (Fig. 12.2).

Figure 12.1 shows the individual elements in the water management system and their main functions. Illustration: NGU.



Performance monitoring of the water management system			
Objects	Surficial infiltration swales and raingarden	Subsurface infiltration I/T-system	Permeable pavement
Lawn mowing	2-26/y		
Removal of mown grass	2-26/y		
Removal of litter	2-52/y	2-52/y	2-52/y
Removal of leaves	2-4/y	2-4/y	2-4/y
Cleaning streets	4-12/y	4-12/y	4-12/y
Sowing	x		
Fertilizing	x		
Verticutting	x		
Fill up low spots	x		x
Removal of silt	x	x	x
Lowering (scraping) of the verge	x		
Replace topsoil layer in rainwater garden/swale	x	x	
x = <i>curative maintenance</i>			

Figure 12.2

Important factors for maintaining the hydraulic performance of SUDS after construction are:

- continued monitoring of infiltration capacities of the SUDS;
- monitoring of groundwater levels (see p.189-191);
- repair of swales under dry conditions;
- mowing of grassed swales only at sufficient dry weather conditions;
- adequate communication towards the citizens.

### Curative versus preventive measures

Curative maintenance is defined as maintenance work which involves the repair or replacement of elements which have failed or broken down. Preventive maintenance includes both performance monitoring and life-extending tasks which are scheduled at regular intervals. In this chapter, we discuss performance monitoring as a separate item, though it can be categorised under preventive maintenance.

Figure 12.2 gives indicative maintenance frequencies for general maintenance of the treatment train at Bryggen. Illustration: NGU.

The choice between curative or preventive measures depends on the following criteria:

- a) direct damage and effects of failure;
- b) insight in causes of reduced function;
- c) effort for collecting and assessing data.

The direct damage and effects of failure of the elements determine whether a preventive or a curative treatment is needed. To determine which preventive measures to take, insight is needed in the mechanisms which cause the elements to fail. For preventive maintenance, one discerns a situation dependent approach - and a use (or time) dependent approach. At a situation dependent approach, investigation will take place into the state of the element. It is necessary that criteria for the functioning of the element have been defined (e.g. “an emptying time of max. 24 hour” or “pollutants must not exceed the reference concentrations”). At a use (time) dependent approach, maintenance takes place after a certain time or a certain load. The choice between a situation dependant or use dependent approach depends on the effort which is necessary to collect and assess data about the state of the object. For the treatment train at Bryggen, both methods will be used, at least until enough knowledge has been gained on the functioning of all elements.

Objects	Surficial infiltration swales and raingarden	Subsurface infiltration I/T-system	Permeable pavement
Visual inspections (mechanical failures, clogging etc.)	1/y	1/y	1/y
Detailed measurement infiltration capacity (emptying)	continuous, sensors	continuous, sensors	-
Simple measurement infiltration capacity	-	-	1/5y
Groundwater sampling	1/5y	1/5y	1/5y
Soil sampling	1/5y	1/5y	1/5y
Stormwater sampling	1/5y	1/5y	1/5y

Figure 12.3

To carry out maintenance measures effectively, insight is needed in the causes of a diminished function of the infiltration facilities. Diminished functioning of SUDS can be defined such as:

- reduction of the infiltration capacity of individual elements;
- reduction of the storage capacity of individual elements;
- reduction of the discharge capacity (in an overflow situation);
- pollution of soil and groundwater.

Practical guidelines for the management of infiltration devices may be implemented in so-called management diagrams, which for each object mention the possible management activities and frequencies. Management diagrams describe the possibilities for investigations, such as inspections or measuring. Good management starts with a good and univocal recording of the basic facts of the elements (such as location, dimensions, fabric, etc.). Also, the main points of the design have to be recorded, as well as the results of inspections and investigations.

Management diagrams indicate which activities are necessary for which element, and at which frequencies. However, the site manager must fine-tune the management with his own experiences, bases on the local situation.

### Performance monitoring of the water management system

Besides regular maintenance, a systematic performance monitoring program has been set up in order to timely identify possible disruptions, such that curative maintenance work can be carried out accordingly, or that adjustments can be made to the regular maintenance program as described.

The infiltration level in the subsurface I/T-system is partly maintained by actively pumping groundwater that leaks through the sheet pile from 2 wells on the inside of the sheet piling and re-infiltrating this water into the I/T-system (chapter 10). During normal to wet meteorological conditions, the infiltration level in the I/T-system is upheld by infiltrating rainfall from connected roofs, roads and connected raingarden and swales. During dry conditions, the groundwater pumps are able to uphold the infiltration level by re-infiltration. During prolonged dry periods, it is optional to use drinking water for infiltration. These active interventions are vulnerable elements of the water management system, caused by leakages in the sheet pile that were beyond repair. It is therefore essential to have a good monitoring system in place to timely identify possible technical failures or other malfunction of the water management system.

It is important to control that

- the groundwater pumps do not operate at tidal levels higher than +0,8 m to prevent salt water intrusion to the pumps and consequential re-infiltration of this water;
- the groundwater pumps do not necessarily operate when the infiltration level is upheld by infiltrating rainfall;
- electrical failures are identified and the site manager is warned.

Figure 12.3 Gives an overview of the performance monitoring actions and frequency for the different elements in the water management system. Illustration: NGU.

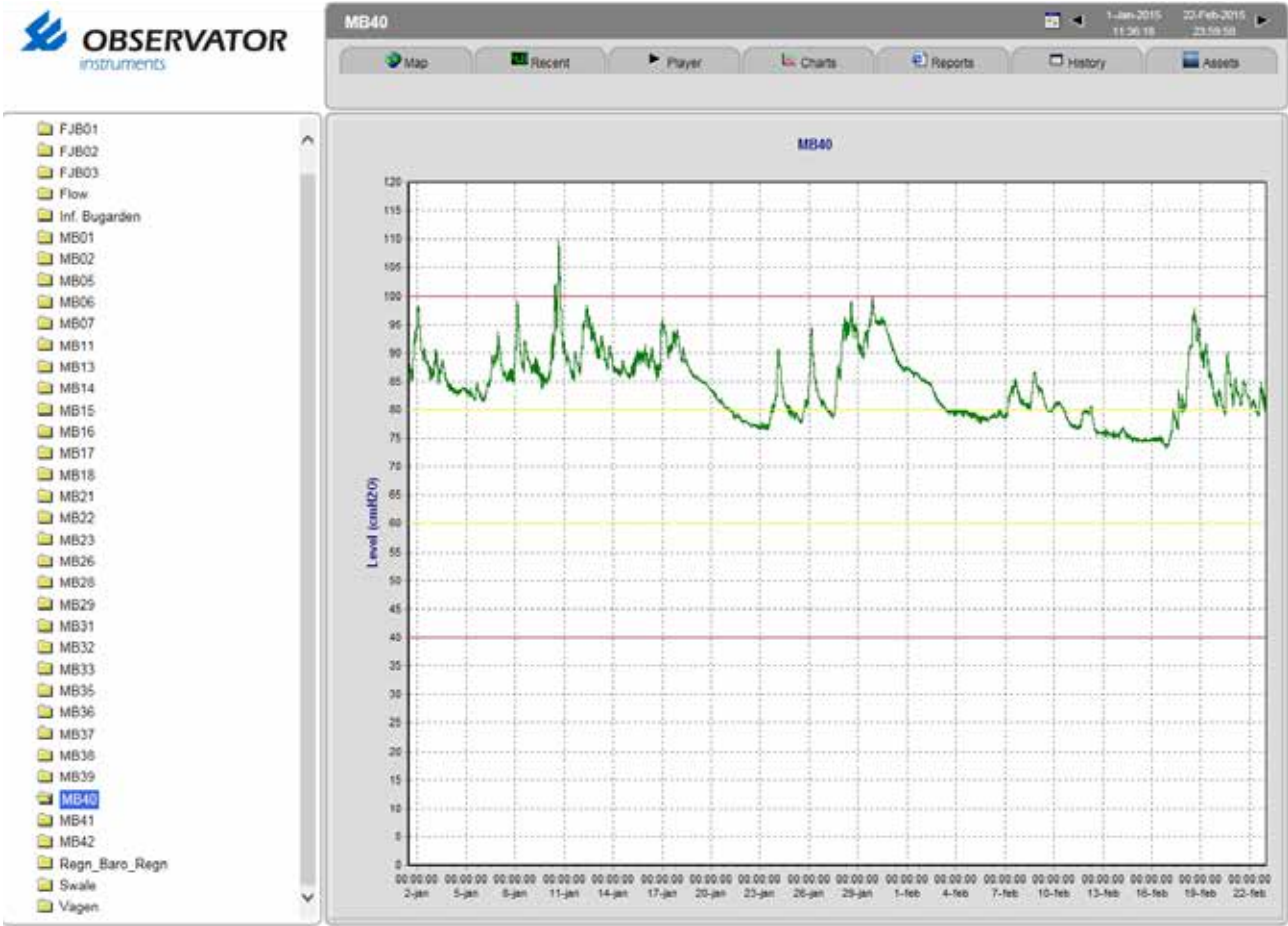


Figure 12.4

The above controls are being carried out by automatic steering with pressure sensors in the infiltration system and in the harbour, connected to an electronic warning system. In addition, pressure sensors in selected groundwater monitoring wells are connected to the warning system (see p.173). The groundwater pumps and electronic steering system will need regular technical maintenance.

**Monitoring of effects in the archaeological deposits**

Monitoring in the unsaturated zone above the groundwater level will continue as long as the existing setup is working, in order to validate the effects of increased infiltration. However, it is not planned to replace the system and sensors if they stop working, both due to the cost involved and due to the disturbance caused to the archaeological deposits, as installation of new sensors require re-opening of a testpit (Fig. 6.9). Replacement (or installation of similar sensors in other areas) will only be carried out if the monitoring of groundwater level or subsidence measurements shows a new, critical development.

The preservation conditions below the groundwater level will be followed by repeated sampling of groundwater from the existing monitoring wells. The cultural deposits underneath Bryggen represent a very large volume, and

it may take decades before the groundwater chemistry for the whole system has reached a new steady state. It is planned to take groundwater samples for analysis from most or all monitoring wells every 3-5 years to follow how the system changes over long time. Besides that, more frequent sampling in selected monitoring wells may be carried out, if specific questions need to be investigated. Finally, the multiparameter probes described in Chapter 6 will continue monitoring until they need replacement.

All these parameters are indicators of the preservation conditions that may be used to estimate the ongoing decay rate (Fig. 6.1). In order to validate this, renewed drillings in selected areas will be carried out at intervals. This will allow a renewed assessment of the state of preservation of the archaeological deposits that can be compared directly to previous assessments, as described in chapter 5.

**The groundwater level**

Monitoring in the saturated zone below the groundwater level will continue in a selected number of monitoring wells, but at a lower frequency. Based on the current knowledge of the hydrogeological situation, a selection of monitoring wells will be made at critical locations. Installed sensors at these locations will continue to register the total (water + air) pressure and temperature in the monitoring wells. Automatic correction for barometric effects will take place using a barometric pressure sensor located at the Bryggen museum. All corrected data are daily published online to a website that is available to the management and relevant users of the site. The database is automatically stored at an online secured server.

Each individual monitoring well has been given “signal values” for high and low groundwater levels. In the optimal situation, the groundwater level varies between those 2 signal values. If groundwater levels drop below the lower signal level, a warning is given through a colouring code in the online system. If needed, for particular critical levels, automatic alarms through sms-messages can be sent to dedicated managers of the system. The same can be done for registered temperatures.

Monitoring wells that have been used during the investigation phase and during the implementation phase of the mitigation measures and that will not be used for long-term monitoring, will not be removed. As mentioned at p.172, those wells will be used for sampling purposes every 3 -5 years. If circumstances indicate, they might need to be re-installed with automatic sensors in the future.

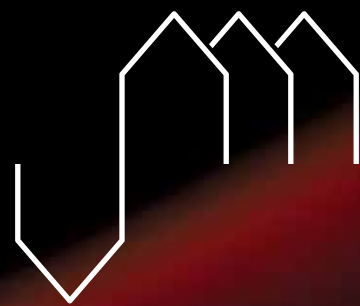
**The subsidence rates**

Monitoring of the subsidence development at Bryggen is recommended as follows:

- From June 2015 annual subsidence measurements and deformation measurements on all measuring points at Bryggen, Schøtstuene and the Hanseatic Museum in Finnegården that are evaluated every second year. Measurement points that have been removed due to works in the area are reestablished in the same points and are reincluded into the schedule from 2015 on.
- One should consider establishing a satellite monitoring programme for Bergen for monitoring of vertical deformations, where Bryggen is included. This could be a good supplement to the subsidence measurement schedule, and could uncover unknown and new threats to the World Heritage site, particularly related to the planning and carrying out of large projects upstream of Bryggen (projects that influence the ground water level), and map at best at an early stage the need for any mitigation measures.

Figure 12.4 An example of the online data presentation. Illustration: NGU.





# 13

BRYGGEN: LESSONS FROM THE PAST,  
MEASURES IN THE PRESENT,  
CHALLENGES FOR THE FUTURE

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# INTRODUCTION

Most people who visit Bergen today will experience the charming harbourfront quarter of Bryggen, which has been listed by UNESCO as a World Heritage Site since 1979, as a touristic historic area that houses museums, shops, restaurants and pubs. Only those people who visit the Hanseatic Museum, with its associated suite of historic buildings 'Schøtstuene', and the Bryggens Museum will discover that this harbourfront area of wooden buildings is much more than that. It actually covers the myriad activities of an important Hanseatic maritime trading settlement that goes back to the Middle Ages. Throughout its rich history, Bryggen has experienced many fires, largely because most buildings were made of wood. The remains of these earlier settlements are to be found stacked one upon the other beneath present-day Bryggen. In 1955, part of Bryggen was yet again destroyed by fire. One outcome was in the shape of the extended archaeological excavations, whose findings were an important addendum to what was already known from the written historical sources. And secondly, it was realized that the rich archaeological deposits remaining under Bryggen represented an important and inseparable part of the heritage site - just as much as the buildings resting on the deposits. In view of this, the challenge confronting the heritage management authorities was to keep preservation conditions as good as possible for both buildings and deposits.

The 1955 fire opened up the possibility for rebuilding the area. In addition to the Bryggens Museum, which houses collections and exhibitions presenting the story of Bergen/Bryggen's past, a large hotel was erected to the northwest of the historic area. It turned out that the inclusion of a service/parking area underneath the hotel was most probably having a serious impact on groundwater levels in the historic area due to leakage through the wall of sheet piling surrounding the construction pit. As the archaeological deposits consist mostly of organic materials, in particular wood, this lowering of groundwater level could have a tremendous negative effect on these deposits' state of preservation.

This was recognized by the local as well as the national heritage management authorities, and with national funding an international research team was established to analyse the problem and to come up with solutions aiming for sustainable in-situ preservation of the archaeological deposits. My aim with this chapter is to provide an overview as well as review of the problems encountered and the measures taken to preserve the site, seen in a wider perspective of modern archaeological resource management.

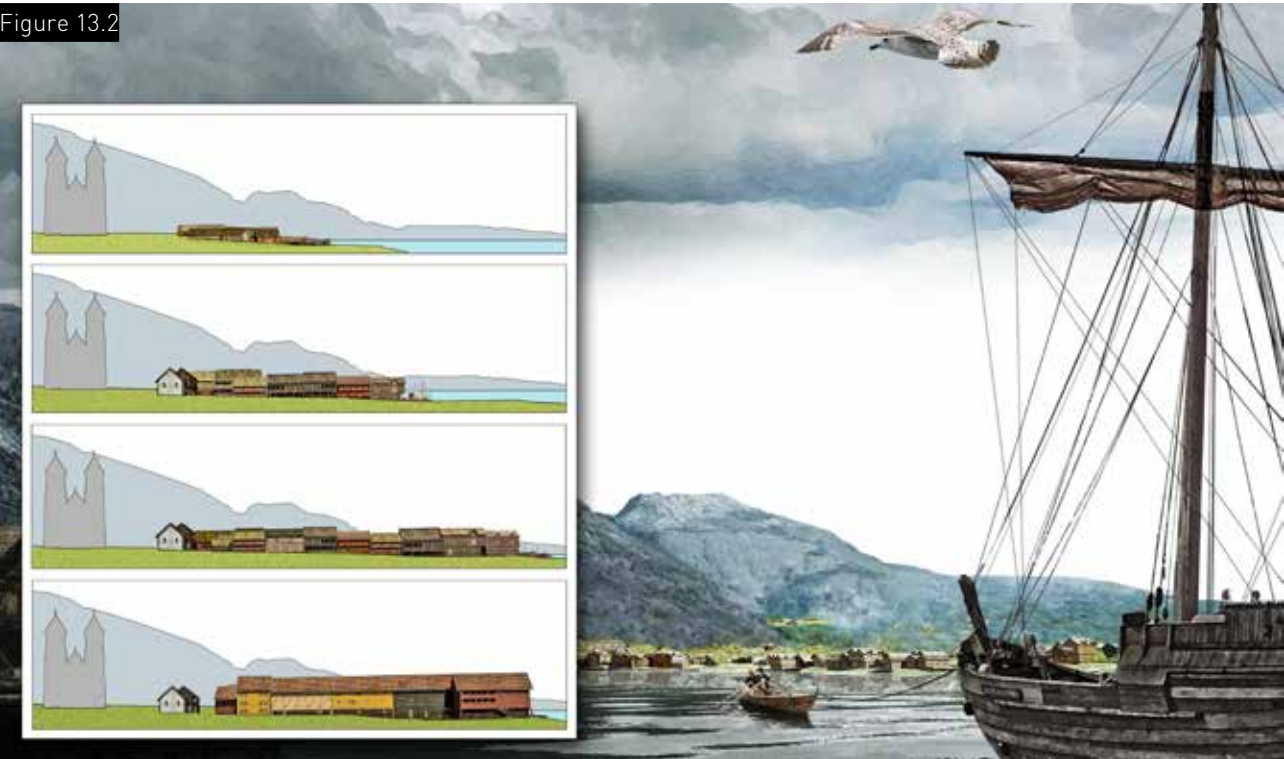
Figure 13.1 Bustling Bryggen. Photo: A. Kjersheim, Riksantikvaren.



Figure 13.1



Figure 13.2



## THE HISTORICAL-ARCHAEOLOGICAL BACKGROUND

In his overview of the history of Bryggen, Professor Geir Atle Ermland places the construction of wharfs in front of tenements to the 12th century. Tenements names in the Bryggen area provide evidence of the historical longevity at Bryggen. An organized community of Hanseatic merchants settled here from the late 13th century onwards and, with the establishment of a major trading outpost of the Hanseatic League in the mid-14th century, the buildings of Bryggen were gradually taken over by Hanseatic merchants, whose warehouses were filled with a variety of bulk goods, such as stockfish from isolated Northern Norway and cereals from Europe.

It was hoped that the extensive excavations that started after the 1955 fire would provide conclusive evidence on the question of the origin of Bergen, or at least of the Bryggen area, but in the end it could only be concluded that traces of activity in the area could be traced back to the first part of the 12th century. Fortunately, the excavations gave us an enormous insight into the daily life of people who lived in medieval Bergen and about the development of Bryggen as an important Hanseatic overseas enclave. They further provided important

information with regard to major events in the area, such as the many historically known fires that offered an accurate means of dating the archaeological deposits, resulting in a unique fire-horizon chronology. Among the several hundred thousand recovered artefacts, which were systematically described and documented during the excavations, more than 6,000 often well-preserved runic inscriptions were found, as Dr Janicke Larsen tells us in her chapter. With translations of the inscriptions on four wooden sticks, she demonstrates the enormous historical potential such messages contain.

The archaeological finds are mainly of organic origin, mostly wood but also bone, leather and so on. Many display a remarkably good state of preservation, and it might be safely assumed that this also holds true for the archaeological deposits underneath the other parts of Bryggen. It is an established fact, however, that these organic deposits are extremely vulnerable to decay under changing conditions in the burial environment.

Figure 13.2 Schematic representation of stages of Bryggen's development, with background panorama. Drawing: T. Sponga, © Riksantikvaren.

## SITE MANAGEMENT: THE PROBLEM

Iver Schonhowd and colleagues relate that during the 1990s property owners at Bryggen started to be aware of building damages caused by subsidence. Measurements showed that in some areas the rate of subsidence was up to 5-7 mm a year. Initially this subsidence was linked to vibration caused by vehicular traffic along Bryggen, but it soon became clear that the groundwater level was lower than before, leading to oxidation of the archaeological deposits - with compaction of these deposits as a result. In order to understand the fall in groundwater level a comprehensive monitoring programme was developed and implemented in 2001, and after some years of monitoring the groundwater level as well as the subsidence, it was hypothesized that the reason for the low groundwater level was leakage into the hotel site. During the building of the hotel, with its underground car park, sheet piling had been rammed down into the ground as a barrier to prevent water penetration and collapse of the construction pit's sides. After the building was finished it was fortunately decided not to remove the sheet piling, because it was assumed that it would prevent or at least restrict leakage of groundwater into the hotel site. However, the leakage turned out to be substantial, and based on the hypothesis that this leakage was the main reason for the low groundwater level in the historic area, investigations to find methods to stop this dewatering were set in motion. In 2009, the engineering company Multiconsult AS was commissioned to analyse the situation and to come up with solutions to stop the leakage, with the ultimate goals of slowing down deposit decay, reducing the rate of subsidence in the upper soil levels, and averting further damages to the historic buildings.

It was mandated that the solutions had to be capable of achieving the following objectives:

- Raising of the water table in the most badly affected areas to levels as close as possible to those existing prior to the hotel's construction (ideally, up to 1 m below the surface)
- Reducing groundwater flow to a minimum
- Reducing the diffusion of oxygen into the ground
- Reducing the rate of subsidence to 1 mm per year or less
- Reducing the average annual temperature in the deposits to 9.0C or less
- Ensuring a minimum of intervention in intact archaeological deposits
- To ensure that the loss of matter does not exceed 0.001% by weight per year as a result of decay and leaching
- Securing, and if possible increasing, the supply of groundwater upstream

Before reviewing the methodology developed and the methods implemented to reach these goals, I will describe the societal context for the in-situ management of archaeological heritage, the concepts and approaches that form the framework for such as the Bryggen project. With the approach it has adopted, the project plays an important role at the forefront of modern archaeological resource management in Europe.

## HERITAGE MANAGEMENT IN A SUSTAINABLE SOCIETY

Professionals working in the field of heritage management are confronted with the basic dilemma of accepting future environmental changes that are accompanied by some regulated loss of our archaeological-historical resources, rather than simply propagating a rigid protection of the present-day remnants of the past. Gradually, these professionals have become aware of the need for a change in strategy, moving from a static - or even defensive - approach towards a more integrated, dynamic, proactive approach to the preservation of the archaeological-historical environment. The 1992 Valletta Convention, which describes how our heritage is to be treated, is a reflection of this, and fits perfectly well into the wider context of the present paradigm of developing a sustainable society.

The classic definition of sustainable development provided by the World Commission on Environment and Development (United Nations 1987) describes it as a development ‘that meets the needs of the present generation without compromising the ability of future generations to meet their own needs’. This has been commented on by many authors, but a widely accepted perception is that sustainable development is the process of ensuring that all people can achieve their aspirations while maintaining the critical conditions that are essential for our collective survival. Defining sustainability is therefore ultimately a social choice about what to develop, what to sustain, and for how long. This notion of sustainability fits remarkably well within modern views on cultural heritage management by replacing the rather static term of cultural heritage management by cultural resource management. This notion is also nicely reflected in the Council of Europe Framework Convention on the Value of Cultural Heritage for Society (Faro 2005) – which up to now, however, has been ratified by only sixteen member states. An important consequence of this approach is that the preservation of our archaeological resources is not purely the domain of researchers and managers in the heritage field, but concerns all decision-making stakeholders who may have any relationship to these resources.

Now we shall return to Bryggen again. There was never any question of taking action against either the hotel developer or the owner; the important thing now was to encourage the latter to become involved as a stakeholder in the process of future planning and development. At the time of the hotel’s construction, the potential negative impact of such projects on the preservation of adjacent archaeological deposits was poorly understood. Heritage management policies were reactive rather than proactive back then, and research-based knowledge in the field of in-situ preservation of archaeological deposits was scarce. In fact, such research did not get started before the 1990s in the United Kingdom, the Scandinavian countries and the Netherlands, and the recommendations in the Valetta Convention were instrumental in getting the ball rolling. This figurative ball has, happily, since turned into a snowball, gaining momentum and mass all the time.

### FROM ACTION RESEARCH TO KNOWLEDGE TRANSFER

Our common cultural heritage has to be considered as a sustainable part of a changing society. This means that linking research-based knowledge to decision-making actions is essential when trying to create solutions to avoid irreversible decay of our archaeological resources. Systems designed to link knowledge to effective action in sustainability have been presented and discussed by several authors concerning various other areas in society, but are also applicable in the field of cultural resource management. However, where knowledge and action in sustainable development of our heritage come face to face, numerous barriers are encountered. Linking knowledge to cost-effective action involves overcoming multi- to transdisciplinary boundaries of quite different cultures of researchers, of policy- and decision-makers at national, regional and local levels, of private bodies, and of the general public. Action for sustainable development of cultural heritage stretches across the full spectrum of scales from global UNESCO agreements to European conventions, and from national legislation to provincial and municipal instructions and strategies. Integrating these scales is not always easy. Linking research-based knowledge on cultural heritage to a regional or local scale of action and implementation can, for instance, be hindered by matters of jurisdiction, since the policies of the institutional bodies responsible for nature and/or water management may have important effects on the cultural heritage strategies of other institutional bodies, which often operate at different governmental levels.

Heritage managers have to cope with these sometimes limiting conditions when making a management plan that describes the methodology for how to preserve a particular site. This also applies to Bryggen, as described in detail by Iver Schonhowd and his colleagues in this publication. However, in the case of Bryggen, we are in the unique position that authorities from different areas and at different levels in the administrative apparatus all acknowledged the need to preserve the site, and ample financial support was made available by the central government to create research-based knowledge that could be utilized and transformed into decision-making actions for sustainable preservation of the site. From this point of view the Bryggen project can act as an example and blueprint for many other sites at risk worldwide!

Figure 13.3 All the project group’s principal members gathered in front of Bryggen.  
Photo: A. Ramstad, Riksantikvaren.

### TOWARDS A MANAGEMENT PLAN: A RISK ASSESSMENT

The difficulty of transcending boundaries between different cultures of research disciplines, in this case between the humanities on the one hand and science and technology on the other, might have proved detrimental to the aspects of problem definition and research design in the early stages of the knowledge–action system. With regard to Bryggen, I conclude that the cooperation between researchers from these disparate disciplines has led to a successful methodological approach in developing solutions to create a management plan for preserving the archaeological deposits as well as preventing further subsidence.

In order to find solutions to the continual loss of water at the Bryggen site, discussions started on how to create a situation that would prevent any form of leakage through the sheet piling. After assessing and comparing all

proposed solutions, it was finally concluded that none could guarantee complete success, and an international team of specialists was formed to gain more insight into the problem, the ultimate goal being to design and implement a number of methods that would, in combination, either prevent or at least compensate for the leakage of groundwater.

The team’s starting point was to conduct a risk assessment of the site in order to define the problem to be solved. This called for an archaeological as well as a hydrogeological-geotechnical approach, while the scientific gap between these disciplines was bridged by specialists familiar with the physico-chemical behaviour of archaeological materials in soils under changing conditions.

As regards the archaeological component, the chapter by archaeologist Rory Dunlop presents the context recording system currently used by NIKU on medieval sites both within and outside the towns; it has been used in connection with the recording of contexts in virtually all of the drillings and test-pits carried out at Bryggen since 2001. The system contains a particular part devoted to the



Figure 13.3



assessment of the state of preservation of all the organic components found in each individual archaeological context, along with an overall assessment of the context as a whole. The system is extremely detailed and part of its strength lies in the fact that numerical values can be assigned to a wide range of variables, including the state of preservation of the various organic components encountered in a context. Based on the accumulated data from NIKU's investigations at Bryggen, Dunlop's conclusion is that the overall situation within the historic site is one of a good state of preservation; however, in one area close to the sheet piling an unexpected and alarming deterioration in state of preservation was detected, even in one of the deepest contexts.

Recognizing decay in the field is one step in the risk assessment of a site. The next important step to be made is to estimate the rate of decay of the heterogeneous materials present in the deposits. Quantification of decay rates is necessary in order to assess whether these materials are likely to survive for centuries, decades or only a few years. Ever since monitoring of the site began in 2001, Dr Henning Matthiesen and his colleagues at the National Museum in Copenhagen have used a three-pronged approach to study decay rates at Bryggen. They investigated and quantified the state of preservation in the archaeological deposits at regular intervals, based partly on the detailed analysis and interpretation of samples of soil and groundwater. They used data on many environmental parameters to define the prevailing preservation conditions in four different parts of the site. And in addition to this, they performed model experiments of decay processes in the field as well as in the laboratory. By combining these three lines of attack, they were able to obtain a more robust understanding of the decay situation at Bryggen and arrive at theoretical estimates of decay rates in the deposits in the site's four main areas. As well as monitoring a number of soil parameters, including temperature, much effort was put in studying the oxidation state and changes in the concentrations of oxygen in the deposits to estimate current and expected future decay under the current groundwater levels. Matthiesen and colleagues opted for the relatively expensive, but direct and precise, measurement of oxygen in the soil, while redox-monitoring specialist Michel Vorenhout's chapter presents his results from an alternative method: the measurement of redox potentials. A high redox potential reflects an aerobic, oxidizing environment, whereas low

values represent anaerobic, reducing conditions. This method is complementary to the direct measurement of oxygen. The two methods' results are in accordance with each other, and show that oxidation of the archaeological deposits, even at quite deep levels, will be a recurrent problem, in particular in dry seasons.

This understanding, however, could only be reached by knowing the hydrogeological situation at the site. The archaeological deposits, up to c. 10 metres thick, that have been preserved for hundreds of years are for the most part situated below groundwater level, in the saturated zone with anoxic conditions. Organic materials are vulnerable to microbial decay, while the most severe and rapid degradation is caused by oxygen-requiring fungi, though other types of microorganisms can cause decay under anoxic conditions, albeit at a much lower rate. As previously mentioned, the presence or absence of oxygen is determined by the water content of the deposits and therefore by the groundwater level. This meant that any risk assessment of the site must also include a detailed study of the hydrological regime of the whole area, as described by Hans de Beer and Anna Seither. In order to improve the understanding of the hydrological system, with special focus on identifying the factors principally influencing preservation conditions, they constructed a 3D subsurface and a numerical groundwater model. These tools helped to promote understanding of the spatial and temporal hydrogeological variations at Bryggen and adjacent areas, with their potential impact on the archaeological deposits. The impact of the sheet piling - and of the underground drainage system below the hotel - on Bryggen's groundwater conditions became very clear and the most vulnerable part of the area could be identified. The whole model proved to be key when it came to developing the appropriate mitigation measures.

The major negative consequence of the lowered groundwater levels, with the associated accelerated oxidation of the organic deposits and loss of archaeological information, is subsidence of the area. The investigations carried out by Multiconsult's Jann Atle Jensen were therefore an essential part of the risk assessment work. He analyzed subsidence measurements from fixed survey points all over the site, points installed both on buildings and in the ground, and found that in

the period between 2000 and 2011 the average rates of subsidence ranged from 1.2 to 4.1 mm per year!

# THE MANAGEMENT PLAN: METHODOLOGY AND METHODS

With all this input from the experts as a solid base a site management plan was developed, described by Iver Schonhowd and colleagues as Operation Groundwater Rescue, which should lead to sustainable preservation of the archaeological deposits.

The purpose of the Groundwater Project was to attain the following principal objectives:

- Raising of the water table in the most badly affected areas to levels as close as possible to those existing prior to the hotel's construction (ideally, up to 1 m below the surface)
- Reducing the rate of subsidence to 1 mm per year or less
- Reducing the average annual temperature in the deposits to 9oC or less
- Ensuring a minimum of intervention in intact archaeological deposits

Mitigation works were initiated late in 2011, starting with the repair/replacement of existing drainage and sewage pipes around the hotel. This was followed by the construction of a water infiltration/transport system along two sides on the outside of the sheet pile wall, accompanied by the closing of holes in the wall. As Dr Kevin Tuttle's chapter makes clear, these measures have been largely successful, though it has been necessary to use tap water to maintain stable groundwater levels during dry periods - a solution that may not be viable in the long run. To increase the system's dry-weather capacity, some storage tanks were emplaced in the grounds of Schøtstuene, and two groundwater pumps are now used to circulate water from the inside of the sheet pile wall, this water coming mainly from deep leaks between the hotel and Schøtstuene. Rainwater falling in areas at the back of Bryggen is captured, cleaned and infiltrated at a retarded rate in a two-part rainwater garden and connected swales, as described in detail in the chapter by water-management consultant Floris Boogaard, preventing this rainwater from merely becoming surface runoff that disappears uselessly into the municipal drainage network. For the same reason, a number of other areas, mainly ones surfaced with cobblestones, have been turned into permeable pavement. This approach - where several different

mitigation measures are combined in an appropriate configuration - is based on recent developments in the stormwater industry, and its application has resulted in a modern, sustainable urban drainage system for Bryggen, a system that is intended to be self-regulating and, ultimately, self-sufficient (i.e., not reliant on the use of tap water). And all these measures are reversible, should this ever be necessary.

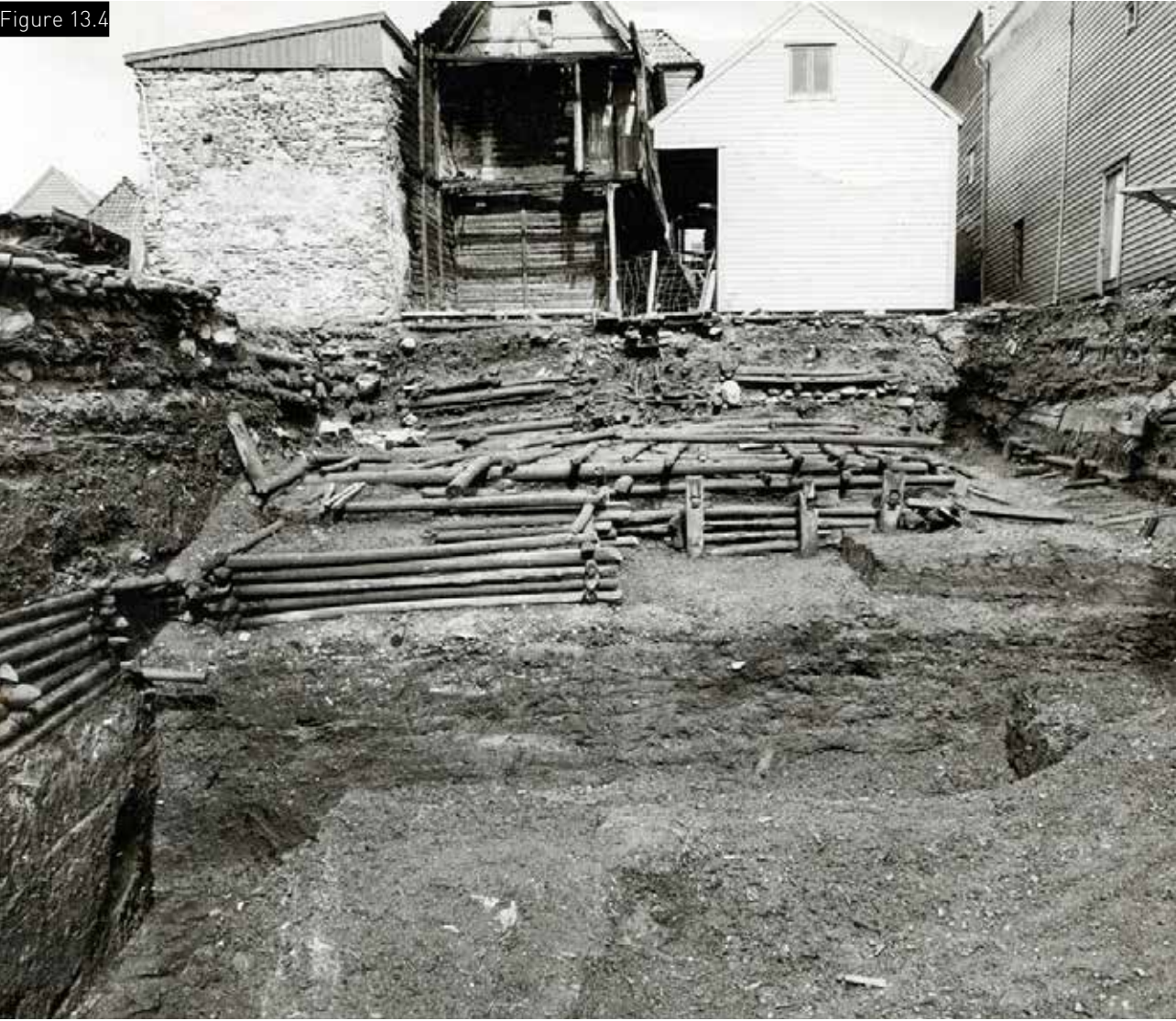
In order to evaluate the effects of the mitigation work, subsidence trends and groundwater behaviour and composition continues to be closely monitored. In deposits lying above groundwater level, the main focus is on detecting changes in oxygen concentrations and redox values, and results so far show that the increased infiltration of water has reduced the presence of oxygen quite significantly. In deposits below groundwater level, the focus is primarily on tracking water-flow rates and on how the groundwater chemistry can be used to model and quantify ongoing decay. Recent data show that the mitigation measures seem to be effective: groundwater levels have been raised substantially, certain areas that had previously been very dynamic - in hydrological terms - have become much more stable, oxygen levels have decreased, and the rate of subsidence has clearly been reduced to a more or less acceptable level; even some uplift has been recorded at a few points. We cannot, however, allow ourselves to become complacent; continued monitoring is required to verify that these positive effects indeed result in stable and sustainable preservation conditions.

# AGENDA FOR THE FUTURE

The agenda to be set for the future has many aspects and several levels, and concerns several target groups. First and foremost, the makers of heritage-management policy should explore their position and attitudes in relation to the arena of economic developments; in this context, the Valetta Convention, along with the Faro Convention, has been and will continue to be of considerable help when it comes to viewing our archaeological heritage not only as a cultural, but also as a societal and an economic phenomenon.

This book deals with the management of a single site, Bryggen, with its combination of visible and invisible remains that relate an almost 1,000-year-long history.

Figure 13.4



The work carried out at Bryggen has demonstrated that research-based knowledge could be successfully linked to processes of decision making and the implementation of mitigation measures to preserve this iconic site. Bryggen-like situations, where modern towns rest on thick archaeological deposits that encapsulate their history, are to be found all over Europe, and we have to realize that we are just at the beginning of developing research-based preservation policies. Acquiring relevant research-based knowledge remains the principal challenge in relation to putting the assessment of the state of preservation of a site's archaeological contexts on a more rigorous scientific and quantitative footing.

The numerical system of assessment that has become standardized practice in Norway could act as a blueprint for use in other countries. All the same, there is always

room for improvement in any system of this kind. In addition to analyses of oxygen concentrations, one possible method for improving state-of-preservation assessments involves studying the state of preservation of the pollen grains found in soil samples taken from selected contexts, which will necessitate input from botanists. The application of soil micromorphology has also proven to be useful in determining the process of oxidation in archaeological deposits. However, an increase in the number and complexity of analytical methods intended to estimate state and rate of preservation at a site will drive up the cost of archaeological resource management substantially,

Figure 13.4 Buildings erected after the 1702 fire on top of metres-thick organic archaeological deposits. Photo: Universitetsmuseet i Bergen.

which has to be carefully considered by the responsible heritage agencies in the different countries, as most of these costs will have to be recovered from other public- and private-sector stakeholders.

With regard to Bryggen, it has been demonstrated that the mitigation measures have had clear results, but it will take another few years before the full effect can be documented. This presupposes that the water management system continues to operate as efficiently as possible the whole time, and Hans de Beer and colleagues have described in the preceding chapter that the implemented SUDS will need some form of scheduled maintenance to avoid malfunction of their key components. The application of these systems in various other countries has yielded a wealth of experience that can contribute to keeping the system at Bryggen running in an optimal fashion.

Equally importantly is the design, performance and funding of the mid- to long-term monitoring system that will provide the data that indicate to what extent goals are being achieved, and that provide feedback on how the water-management system is functioning from day to day.

Although the activities are closely connected, the authors distinguish between monitoring of (i) the archaeological deposits, (ii) groundwater levels, and (iii) subsidence. It has been suggested that in the long run it will not be necessary to maintain monitoring of the deposits themselves at an intensity similar to that of today. The argument here is that as long as groundwater levels and water quality are monitored, these results can be used as proxy indicators of the deposits' condition. From the viewpoint of cost efficiency, this seems to be a reasonable approach. The same applies to the long-term monitoring of subsidence in the area, as one may assume that constantly higher groundwater levels will reduce subsidence rates. However, the historic buildings are also subject to subsidence due to the decay of their foundations, which are largely wooden. This can cause severe damage - and it is a threat that will persist until all the old timber foundations have been replaced with new ones. I wholeheartedly support the suggestion by Jann Atle Jensen, and endorsed by de Beer and others, to introduce a satellite monitoring system as a supplement to the current subsidence-measurement schedule. In addition to this, I suggest raising the monitoring programme's visibility in the neighbouring Bryggens Museum by, for instance, installing a display

unit that shows the groundwater-level measurements more or less in real time. This in order to raise awareness among members of the public that archaeology consists of much more than traditional activities such as the collection and exhibition of artefacts, and that it increasingly depends on far-sighted management of the deposits just below their feet, deposits that are a storeroom of our common heritage.

Summing up, the Bryggen site with the archaeological deposits in particular has experienced a tremendous amount of attention, first of all by archaeologists, dating back to 1955 when the excavations begun. The results underpinned the importance of the site. The effects of the hotel building in the late 1970s/early 1980s, effects that unfortunately did not manifest themselves appreciably until right at the end of the 20th century, reinforced the interest in the site, but now increasingly from the heritage management perspective. The deterioration of the site brought a wide range of stakeholders together in order to protect the site from further decay. Ample financial resources were made available to start the knowledge-action chain, and based on a long-running, multidisciplinary research programme to assess the type and degree of the threats to the site, a complex water-management system was developed and implemented from 2011 onwards. The preliminary results provide encouraging signs that raising groundwater levels is an effective strategy to combat oxidation and decay of the archaeological deposits and thereby reduce the risk of subsidence. The sustainability of the mitigation measures will be verified by a cost-effective programme for monitoring groundwater levels and subsidence trends.

By virtue of all these well-coordinated efforts, Bryggen has become an unique site with regard to archaeological-historical resource management in Europe. It is certainly true that a lot of good work is being done in many UNESCO world heritage sites all over the world to preserve and restore them. However, most of these sites represent a visible heritage that has great attractiveness to a large international public. In the Bryggen case all the efforts were carried out to preserve both the visible and invisible heritage. From that point of view I cordially advise UNESCO to make full use of the Bryggen site as a shining example of what can be done when it comes to preserving our invisible archaeological-historical resources with the help of national and local heritage management bodies and associated stakeholders.



ENDNOTES

GLOSSARY

REFERENCES

BIOGRAPHIES

## ENDNOTES

1 NgL 2 p. 241. Helle 1992, 19.  
2 Msk, Fsk, Hmkr.  
3 Sørlie 1957, 28-29.  
4 Munch 1849, 27-29.  
5 Storm 1899, 436.  
6 Koren Wiberg 1921, 14-33, 46-51.  
7 Ersland 2010, 30-36.  
8 Lorentzen 1952, 11, 63.  
9 Herteig 1969, 139.  
10 Helle 1982, 99-113.  
11 Krzywinski 1984, 36.  
12 Hjelle 1986, 61-62.  
13 Myrvoll 1987, 105-107. Myrvoll's hypothesis was based on the results presented by Dunlop, A.R. 1985. Report on the excavations at BRM 202, Nikolai kirkealmenningen, 1984. - Riksantikvaren, Bergen.  
14 Hansen 2005, 128-134, 221-224.  
15 Helle 1992, 24-27. 2005, 22.  
16 Helle 1982, 162-170, 346-353.  
17 Ersland 2011a, 199-201.  
18 Ersland 2011a, 209.  
19 Ersland 2011a, 155, 158-159.  
20 Ersland 1989, 47-48.  
21 Herteig 1969, 93-94, 101, 116, 150.  
22 Herteig 1969, 50, and 1985a, 29.  
23 Edvardsen, 391-392.  
24 Koren Wiberg 1908, 4-11, 16-17, 1921, 121-130. Lorentzen 1952, 110-143. Helle 1982, 228-246, 703-714. Ersland 2011a, 61-71.  
25 Ersland 2011a, 125-126, 131-132.  
26 Ersland 2011a, 61-66.  
27 Ersland 2005a, 44.  
28 Helle 1982, 732.  
29 Ersland 2011b, 26-28.  
30 Bruns 1900, 380-381.  
31 Edvardsen 96, 373-441.  
32 Holberg 1737, 202-288.  
33 Hanseaterne og Bergen, 1932.  
34 NgL 2,. 241.  
35 Helle 1982, 231.  
36 Ersland 2011a, 61-60.  
37 NgL 2,. 245-246.  
38 Helle 1998, 59-60.  
39 Koren Wiberg 1908, 5. UBB Diplomsamlinga 21.06 1562. NgL 2. R, 2,. 687.  
40 Helle 1998, 61-63.  
41 Helle 1982, 708.  
42 Lorentzen 1952 104-106.  
43 Ersland 2005a, 50.



44 NM II, 25. Edvardsen 391-392. Helle 1982, 706-710.  
45 NRR VIII, 23. Fossen 1979, 280.  
46 AHL Bgf 536.  
47 Holberg 1737, 286-288.  
48 Ersland 2008, 23.  
49 NgL 2,. 243.  
50 Ersland 2011a, 61-62.  
51 Ersland 2005b, 51.  
52 Herteig 1985a, 28-29.  
53 Koren Wiberg 1908, 22-31, 148-151.  
54 Ersland & Trebbi 2010, 19-22.  
55 Lunde 1991, 21-22.  
56 Hommedal 1990, 175.  
57 Lunde 1991, 22.  
58 Hansen 2005, 4.  
59 E.g. Ersland in this publication.  
60 Øye 1998, 9.  
61 Helle 1998.  
62 Herteig 1990, 46 tab. 2.  
63 Jennings and Rogerson 1994, 116-118.  
64 Jennings and Rogerson 1994, 116-118.  
65 Larsen 2013, 44.  
66 Jennings and Rogerson 1994, 116-118.  
67 Høiaas <http://prosjektbryggen.no/skattkammeret/spor-av-ord/>  
68 Liestøl 1980, 21.  
69 Sverris saga, 135, 178.  
70 BRM 31413.  
71 Liestøl 1980, 73-77.  
72 [http://snl.no/Sju\\_sovere](http://snl.no/Sju_sovere)  
73 Liestøl 1980, 74-75.  
74 FNFM Årbok 1927.  
75 [http://no.wikipedia.org/wiki/Eksplosjonen\\_p%C3%A5\\_V%C3%A5gen](http://no.wikipedia.org/wiki/Eksplosjonen_p%C3%A5_V%C3%A5gen) .  
76 Lidén 2012.  
77 ICOMOS NORWAY 2000.  
78 Forente Nasjoner 1987.  
79 Miljøverndepartementet 2005.  
80 Miljøverndepartementet 2013.  
81 Riksantikvaren 2012, 8-9.  
82 European Standard (2012) CEN- EN 16096:2012, Conservation of cultural property, Condition survey and report of built cultural heritage.  
83 Hordaland fylkeskommune 2005  
84 Herteig 1969;1985a;1991.  
85 Christensson et al.2004.  
86 Jensen og Stordal 2004.  
87 Mathiesen 2010a.  
88 Christensson et al. 2008.  
89 Norsk standard 2009.  
90 SINTEF 2009.  
91 Ashley et al. 2012.  
92 Urban Watch og nytt NGU-prosjekt eller Vågsbunnen.

93 Jensen 2009.  
94 Christensen 2010.  
95 Dunlop 2011b.  
96 Norsk standard 2009 (English version issued 2012).  
97 Dunlop 2008c.  
98 Dunlop 2010.  
99 Dunlop 2008b.  
100 Dunlop 2012.  
101 Dunlop 2008d.  
102 Dunlop 2013.  
103 Dunlop 2008c, 7-10.  
104 Dunlop 2011 Dunlop 2011a.  
105 Dunlop 2012, 19.  
106 Matthiesen 2012,. 21.  
107 Koren Wiberg 1939.  
108 Koren Wiberg 1921.  
109 Dunlop 2008a, 14.  
110 Dunlop 2010, 17.  
111 Dunlop 2010, 16.  
112 Dunlop in prep. 2015.  
113 Norsk standard 2009.  
114 Matthiesen, H. 2014a  
115 Matthiesen, H. 2004  
116 Gregory, D., Helms, A. C. & Matthiesen, H. 2009. Björdal, C. 2008.  
Klaassen, R., et al. 2005.  
117 Matthiesen, H., et al. 2008  
118 Hollesen, J. & Matthiesen, H. 2014. Matthiesen, H. & Hollesen, J. 2013.  
Matthiesen, H., et al. 2014b.  
119 Hollesen, J. & Matthiesen, H. 2014.  
120 Hollesen, J. & Matthiesen, H. 2012  
121 Hollesen, J. & Matthiesen, H. 2014  
122 Matthiesen, H., et al. 2014b  
123 Hollesen, J. & Matthiesen, H. 2014  
124 Hollesen, J. & Matthiesen, H. 2014  
125 Matthiesen, H., et al. 2014b  
126 de Beer, J. & Matthiesen, H. 2011  
127 Gregory, D., Helms, A. C. & Matthiesen, H. 2009  
128 Björdal, C. 2008  
129 Matthiesen, H., Zimsen, R. V. & Mortensen, M. N. 2013. Mortensen, M. N., Zimsen, R. V. & Matthiesen, H. 2013  
130 Matthiesen, H. 2010a  
131 Mortensen, M. N., Zimsen, R. V. & Matthiesen, H. 2013  
132 Matthiesen, H. 2010a  
133 Matthiesen, H., Zimsen, R. V. & Mortensen, M. N. 2013  
134 Golmen, L. G. 2005  
135 Matthiesen, H. 2010b  
136 Matthiesen, H. 2010b  
137 Matthiesen, H. 2008  
138 de Beer, J., Matthiesen, H. & Christensson, A. 2012  
139 Matthiesen, H. 2014b

140 Matthiesen, H., et al. 2014a  
141 Stumm, W. & Morgan, J. J. 1996  
142 Appelo, C. A. J. & Postma, D. 2005  
143 Schüring, J., et al.2000 så det står Schüring, J. et al.2000.  
144 DeLaune, R. D., Jugsujinda, A. & Reddy, K. R. 1999  
145 Masscheleyn, P. H., Delaune, R. D. & Patrick, W. H 1991  
146 Mitsch, W. J. & Gosselink, J. G. 2000  
147 This question was addressed in the NSF project "Urban Watch 2011-2015".  
148 Vorenhout, M., et al. 2004. Vorenhout, M., van der Geest, H. G. & Hunting, E. R. 2011.  
149 See [https://en.wikipedia.org/wiki/Down-the-hole\\_drill](https://en.wikipedia.org/wiki/Down-the-hole_drill) and [https://en.wikipedia.org/wiki/Drilling\\_rig](https://en.wikipedia.org/wiki/Drilling_rig) for more explanation.  
This type of rig has the capability of describing the soil profile by recording the drill resistance.  
150 Eh is used for the standardized version, according to the formula  $E_h = E_m + E_{ref}$ , where  $E_m$  is the measured value, and  $E_{ref}$  is the potential of the standard reference used.  
151 Data was both stored on the internal SD card of the Hypnos data logger, and transferred via a wireless connection over FTP to a data server.  
152 Stumm, W. & Morgan, J. J. 1996  
153 Matthiesen, H., et al.2014b  
154 Hollesen, J. & Matthiesen, H. 2014  
155 As measured at the Florida meteorological station near Bergen.  
Data from <http://www.yr.no/place/Norway/Hordaland/Bergen/Bergen/statistics.html>  
156 De Beer, J. 2005. De Beer, J. 2008.  
157 De Beer & J.; Matthiesen, H. 2011  
158 Jensen, J.A. & Stordal, A.D. 2004  
159 De Beer, J. 2010  
160 De Beer, J. 2008  
161 De Beer, J. 2010  
162 De Beer, J., et al. 2007. De Beer, J., Price, S.J., Ford, J.R. 2012.  
163 Norconsult AS 2011  
164 De Beer, J. & Tuttle, K.J. 2014  
165 Rory Dunlop, pers. comm., January 21, 2015  
166 de Beer J., Christensson A. & Boogaard F., 2012  
167 Matthiesen H., et al. 2014b  
168 Dunlop, R., 2004–13  
169 Gremmertsen C., June 2013  
170 Gremmertsen C., June 2013  
171 Boogaard F.C., et al. 2014a  
172 Boogaard F.C., et al. 2014a  
173 Boogaard F.C, et al. 2014a  
174 Fletcher T.D., Andrieu H., Hamel P., 2013  
175 Boogaard F., et al 2007  
176 Ashley R., et al 2012  
177 Boogaard F.C, 2015  
178 Boogaard F.C,et al. 2007  
179 Regnbed - samler opp og infiltrer lokalt overvann, Project poster 2014  
180 Boogaard F.C, Jeurink N.,Gels J.H.B. Utrecht, 2003

181 CIRIA (2004)  
182 Boogaard F.C., et al. 2014b  
183 Leguijt B., 2013  
184 Boogaard F.C., 2015  
185 Boogaard F.C., et al 2014b  
186 CIRIA 2004  
187 ANKO AS, 2014.  
188 Graphs taken from reference ANKO AS, 2014. Graphs received from NGU (Anna Seither and Hans de Beer)  
190 Graphs taken from reference ANKO AS, 2014. Graphs received from NGU (Anna Seither and Hans de Beer)  
191 Graphs taken from reference ANKO AS, 2014. Graphs received from NGU (Anna Seither and Hans de Beer)



## GLOSSARY

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**Aerobic decay** - the decay of organic material by organisms that require oxygen

**Anaerobic decay** - the decay of organic material by microorganisms that do not require oxygen

**Anoxic** – without oxygen present

**Archaeological deposits** – all sub-surface sediments and remains deriving from human activity ('anthropogenic'); sandwiched between geological deposits and modern surface deposits

**Bentonite barriers** - subsurface bentonite (clay) dams constructed to locally withhold groundwater flow and raise the groundwater level to a regulated level

**Catchment area** - also called drainage basin, is an extent or an area of land where surface water from rain, melting snow, or ice converges to a single point at a lower elevation, usually the exit of the basin

**Context** - basic unit of archaeological stratigraphy

**Conventional drainage** – the traditional method of draining surface water using subsurface pipes and storage tanks

**Dipwell** - term formerly used for “monitoring well”

**Drilling rig** - a large machine which creates holes in the earth sub-surface. Used for the installation of monitoring wells and taking samples for archaeological soil descriptions

**Dry swale** - shallow vegetated channel with filter in the base to convey surface runoff to the sewer network or infiltrate into the surrounding soils

**Electron receptor** - a chemical that can take up an electron. Needed in decay of organics and redox processes

**Filtration** - the act of removing sediment or other particles from a fluid by passing it through a filter

**Filter drain/IT Drainage** - a linear drain consisting of a trench filled with a permeable material, often with a perforated pipe in the base of the trench to assist drainage

**(Ground)water divide/watershed** - border between two (ground)water reservoirs, represented by a local maximum (ground)water level

**Hydrogeology** - the area of geology that deals with the distribution and movement of groundwater in soil and rocks.

**Infiltration/re-infiltration** - putting water into the ground (by any means)/ recycling, by pumping, of water that has already been infiltrated

**Infiltration device** - a device specifically designed to aid infiltration of surface water into the ground

**Inside sheet pile wall** - the hotel site, encircled by sheet piling (also applies to the site of Bryggens Museum)

**m asl** - metres above sea-level (datum Norwegian Normal 1954). Average sea level in Bergen is +0.01 m above the agreed national reference height NN1954

**Mitigation work** - set of measures undertaken in connection with re-establishing a stable groundwater situation

**Monitoring** - the combination of all measurements at the Bryggen site. Monitoring here includes all parameters measured, and the integration of those into the advice delivered to the Directorate for Cultural Heritage. At Bryggen, the term monitoring is used for all fases of measuring.

**Outside sheet pile wall** - area containing in-situ archaeological deposits (including the Bryggen World Heritage site)

**Oxic** - with oxygen present

**Permeable pavement** - a permeable surface that is paved and drains through voids between solid parts of the pavement

**Preservation conditions** - the set of environmental factors that govern the preservation of archaeological material

**Rain garden** - a planted basin designed to collect and clean runoff (normally from a roof or hardstanding with low risk of pollution)

**Redox potential** - the potential for reduction or oxidation in a substance/soil. Describes the potential for fast or slow degradation of organic archaeology

**Saturated zone** - the part of the soil column that is permanently water-filled

**Schøtstuene** - suite of (relocated) historic buildings situated in separate area between the hotel and St. Mary's Church

**State of preservation** - current condition (in relation to degree of decay) of an archaeological context and/or its organic constituents, assessed by archaeologist (based on visual, tactile and olfactory examination)

**Stepwise infiltration-transport (I/T-) system** - the subsurface IT-system in Bugården

**Subsidence** - the gradual sinking of an area of land. Subsidence can result from fluid (e.g. groundwater) withdrawal in weakly consolidated materials or from loss of organic material in the ground. The loss of fluid or organic material causes consolidation of the empty pore spaces, which means that any voids in the soil previously filled with fluid or organic material are compressed by the mass of the overlying materials, effectively decreasing the soil volume and resulting in subsidence. In the case of structures with shallow foundations, such as at Bryggen, the soil will 'move away' from beneath the structures, taking away their support and allowing them to move

**Swale** - a shallow vegetated channel designed to conduct and retain water, but may also permit infiltration. The vegetation filters particulate matter  
**Tenement, double** - two rows made up of a (variable) number of separate but contiguous buildings running at right angles to the waterfront and served by a passageway running between the paired rows

**Tenement, single** - a single building row running at right angles to the waterfront and served by a passageway running along one side of the row

**Unsaturated zone** - the part of the soil column above the groundwater level where soil pores include both water and air

**Vågen** - Bergen's harbour bay

**Vågsbunnen** - a historic quarter of Bergen; extends southeastwards from Bryggen

**Water management system** - all systems required to handle, treat, infiltrate and discharge water at Bryggen

**Zone of groundwater fluctuation** - the part of the soil column where the groundwater level varies as a consequence of natural meteorological variations and artificial groundwater extraction or infiltration.

**Øvregaten** - the High Street, running along the back of the Bryggen area



## REFERENCES

Absalon Pederssøn. [1895]. Om Norgis Rige. In *Historisk-Topografiske Skrifter om Norge og norske Landsdele, forfattede i Norge i det 16de Aarhundrede*. Ed. G. Storm. Kristiania.

AHL = Archiv der Hansestadt Lübeck.

ANKO AS (2014) Bryggen i Bergen. Bevegelsesmålinger august 2014. Jobb nr. 2011081. Dokumentnr. 6». *Preliminary report*. Bergen. 47 p.

Appelo, C. A. J. & Postma, D. [2005] *Geochemistry, Groundwater and Pollution* Second Edition. Taylor & Francis. 649 p. 2005. doi:10.1201/9781439833544.

Ashley R., et al. (2012) Selling sustainability in SKINT (SSIS), *SKINT water series II. 56 p.*

Björdal, C. [2008] *Mätning av nedbrytningshastighet i miljöbrunnar - en pilotstudie*. Report no 2008:48. Bremerhaven. SP Sveriges Tekniska Forskningsinstitut.

Boogaard, F. C. [2015] Stormwater characteristics and effectiveness of sustainable urban drainage systems in The Netherlands.

Boogaard, F. C., Jeurink, N. & Gels, J.H.B. [2003] Vooronderzoek natuurvriendelijke wadi's, Inrichting, functioneren en beheer. ISBN nummer 90.5773.207.6, Utrecht.

Boogaard F.C., et al. [2007] *Design, implementation and maintenance of Sustainable Urban Drainage Systems*. ISBN 978.90.5773.369.7, STOWA 2007-20, Utrecht, The Netherlands [in Dutch].

Boogaard, F.C., et al. [2014c] Evaluating the infiltration performance of eight Dutch permeable pavements using a new full-scale infiltration testing method. *Water* 6. P.2070–2083. <http://dx.doi.org/10.3390/w6072070>.

Boogaard, F.C., et al. [2014b] Lessons learned from over two decades of global swale use, *13th International Conference on Urban Drainage, Sarawak, Malaysia, 7-12 September 2014*, ICUD 2014.

Boogaard, F.C., et al. [2014a] Selection of SUDS based on storm water quality characteristics, *Challenges* 2014, 5(1). P.112-122; doi:10.3390/challe5010112 <http://www.mdpi.com/2078-1547/5/1/112>.

Brattegård, O. [1943] Namni på dei gamle gardane på bryggja i Bergen. In *Historisk Tidsskrift* 33, 1943-46. Oslo. P.257-285.

Bruns, F. [1900] *Die Lübecker Bergenfahrer und ihre Chronistik*. Berlin.

Christensen, S. [2010] *Bryggen i Bergen. Kvalitetssikring av Multiconsults forprosjekt for tetting av grunnvannslekkasje*. SINTEF Byggforsk, 2010.

Christensson, A., et al. [2004] *Safeguarding historic waterfront sites: Bryggen as a case*. Culture 2000. Stiftelsen Bryggen/Politechnika Szczecina, Szczecin. 336 p.

Christensson, A., et al. [2008] *Peleprosjektet. Volume 1. FoU-prosjekt Riksantikvaren 2005-2007*. Oslo, Riksantikvaren. 65 p.

CIRIA [2004] *Sustainable drainage systems; hydraulic, structural and water quality advice*. CIRIA, UK.

De Beer, J. [2005] *Hydrogeologisk modellering Bryggen, Bergen: midlertidig rapport*. NGU report 2005.080. [in Norwegian only]

De Beer, J. [2008] *Statusrapport grunnvannsovervåking og hydrogeologisk modellering ved Bryggen i Bergen*, NGU report 2008.069. [in Norwegian only]

De Beer, J. [2010] *FoU-prosjekt grunnundersøkelser og setningsmålinger*. Multiconsult, avd. Noteby. Notat vedrørende først resultater heving drenssystem v/ SAS hotellet, november 2010, 1. desember 2010, ref. 10/00067-30. [in Norwegian only].

De Beer, J., et al. [2007] A numerical model to support archaeological preservation strategies. In Kars, H. & Robert M. Van Heeringen (eds.) Journal of Bio- and Archaeological Studies 10. *Preserving archaeological remains in situ. Proceedings of the 3rd conference 7-9 december 2006*, Amsterdam.

De Beer, J. & Matthiesen, H. [2011] *Overvåkingsplan for undergrunnen ved Bryggen i Bergen*. Geological survey of Norway NGU. Report no 2010.040.

De Beer, J., Christensson, A. & Boogaard, F. [2012] Sustainable urban water planning across boundaries, *SKINT water series I*.

De Beer, J., Matthiesen, H. & Christensson, A. [2012] Quantification and visualisation of in situ degradation at the world heritage site Bryggen in Bergen, Norway: *Conservation and Management of Archaeological Sites. 14*. P.215-227.

De Beer, J., Price, S.J. & Ford, J.R. [2012] 3D modelling of geological and anthropogenic deposits at the World Heritage Site of Bryggen in Bergen, Norway. *Quaternary International 251*. P.107-116.

De Beer, H. & Tuttle, K.J. [2014] *Styring av infiltrasjonsanlegg ved Bryggen i Bergen*. NGU-notat. 3. juni 2014, 3 s., Statsbygg.

DeLaune, R. D., Jugsujinda, A. & Reddy, K. R. (1999) Effect of root oxygen stress on phosphorus uptake by cattail. *Journal of Plant Nutrition 22*. P.459–466.

Den norske So = *Norske Magasin II*. Utgitt av N. Nicolaysen. Christiania 1868.

DN = *Diplomatarium Norvegicum*. Eds. C.C.A. Lange, C.R. Unger o.fl. Chra. 1849-.Oslo.

Dunlop, A. R. [2004–13], *The Bryggen Monitoring Project*. parts 1–18, reports from NIKU, Archaeological Department.

Dunlop, A. R. [2008a] *The Bryggen Monitoring Project, Part 2: Archaeological investigations in connection with monitoring project, Bredsgården tenement, Bryggen, Bergen, 2002-3*. Oppdragsrapport 66/2008. Bergen, NIKU (revised edition of original report).

Dunlop, A. R. [2008b] *The Bryggen Monitoring Project, Part 4: report on the archaeological investigation of five dipwell boreholes, 2005*. Rapport 28/2008, NIKU, Archaeological Department.

Dunlop, A. R. [2008c] *The Bryggen Monitoring Project, Part 5: report on the investigations at the rear of Nordre Bredsgården, 2006*. Rapport 22/2008 NIKU, Archaeological Department..

Dunlop, A. R. [2008d] *The Bryggen Monitoring Project, Part 6: report on the archaeological investigation of three dipwell boreholes, Bryggen, 2006*. Rapport 63/2008. NIKU, Archaeological Department.

Dunlop, A. R. [2010] *The Bryggen Monitoring Project, Part 10: report on the archaeological investigation of three dipwell boreholes, Bugården/ Bredsgården, Bryggen, 2009*. Oppdragsrapport 36/2010, NIKU, Archaeological Department.

Dunlop, A. R. [2011a] *The Bryggen Monitoring Project, Part 12: report on the archaeological investigation of two dipwell boreholes, Bryggestredet and Bellgården, Bryggen, 2011*. Oppdragsrapport 271/2011, NIKU, Archaeological Department.

Dunlop, A. R. [2011b] *The Bryggen Monitoring Project, Part 13: report on the archaeological investigations in connection with re-infiltration measures, Bryggen, 2011*. Oppdragsrapport 297/2011, NIKU, Archaeological Department.

Dunlop, A. R. [2012] *The Bryggen Monitoring Project, Part 14: report on the archaeological investigation of four dipwell boreholes, Bryggen, 2011-12*. NIKU Oppdragsrapport 70/2012.

Dunlop, A. R. [2013] *Nordre Bredsgården, Bryggen: auger drilling for Urban WATCH, 2013*. NIKU Oppdragsrapport 99/2013.

Dunlop, A. R. in prep. *Report on the archaeological fieldwork in connection with the Groundwater Project, Bryggen in Bergen, 2012-15*. NIKU Oppdragsrapport 16/2015.



Edvardsen, E. (1951-52) Bergen udi Norrige. Del I og II (1674-94). Utg. Olav Brattegard. *Bergen Historiske Forenings Skrifter. Særtrykk 55-58*. Bergen.

Ersland, G.A. (1989) *Eit forsøk på rekonstruksjon av grunneigefordelinga i Bergen ved utgangen av seinmellomalderen*. Upublisert hovedoppgåve i historie UB, våren 1989.

Ersland, G. A. (2005a) Was the Kontor in Bergen a topographical closed enity? In: *Veröffentlichungen zur Geschichte der Hansestadt Lübeck. Herausgegeben vom Archive der Hansestadt. Reihe B. Band 41*. Lübeck.

Ersland, G. A. (2005b) „Saa langt vtt vppa Siøen...” Utfylling og utbygging i Vågen i Bergen frå høg mellomalderen og til midten av 1600-talet. In: Nordeide, S.W. (ed.) *Fra vernesone til risikosone. Studier i middelalderbyene Bergen og Tønsberg randsoner*. NIKU Tema 14. Oslo. P. 46-60.

Ersland, G. A. (2008) Neue Studien zum Archive und Sprache der Hanseaten. In: *Det hanseatiske Museums Skrifter nr. 28. In: Ersland, G. A. & Trebbi, M. (eds.)*. Bergen.

Ersland, G. A. & Trebbi, M. (eds.) (2010) Det hanseatiske Museum 1872-2010. In: *Det hanseatiske Museums Skrifter nr. 29*. Bergen.

Ersland, G. A. (2010) Bergen, Bryggen, hanseatene og Koren Wiberg. In: Ersland, G. A. & Trebbi, M. (eds.). Det hanseatiske Museum 1872 – 2010. *Det hanseatiske Museums Skrifter nr. 29*. Museum Vest, Bergen.

Ersland, G. A. (2011a) *Kven eigde byen*. Bygrunnlegging, grunneige og grunnleige i Bergen og eit utval nordeuropeiske byar. Dreyers forlag, Oslo. 238 p.

Ersland, G. A. (2011b) Das Kaufmannshaus – det hanseatiske kontorets rettslokale og administrasjonshus i Bergen. *Det hanseatiske Museums Skrifter nr.30*. Bergen.

European Standard (2012) CEN- EN 16096:2012, *Conservation of cultural property, Condition survey and report of built cultural heritage*.

Fletcher, T.D., Andrieu, H. & Hamel, P. (2013) Understanding, management and modelling of urban hydrology and its consequences for receiving waters; a state of the art. In: *Advances in Water Resources*, 51. P.261-279.

Forente Nasjoner (1987) *Our common future*. Report of the World Commission on Environment and Development. 300 p.

Innberetning fra den antikvariske bygningsnevnd. Foreningen til norske fortidsminnesmerks bevaring. Årbok 1927. P.75-140.

Fossen, A. B. (1979) *Borgerskapets by 1536 – 1800*. In Bergen bys historie, 2. Bergen, Universitetsforlaget. XVI. 934 p.

Gremmertsen, C. (2013) *Characterisation of the stormwater in The Bryggen catchment - A thorough study of Norwegian urban pollutants and its impact on decomposition of archaeological remains*. Master thesis, Norwegian University of Science and Technology. 124 p.

Golmen, L. G. (2005) *Bryggen in Bergen. Vassinntrenging i fundament og bolverk. Resultat av målinger vinteren/våren 2005*. Report no 5047-2005. Oslo, Norwegian Institute for Water Research NIVA.

Gregory, D., Helms, A. C. & Matthiesen, H. (2009) The Use and Deployment of Modern Wood Samples as a Proxy Indicator for Biogeochemical Processes on Archaeological Sites Preserved in situ in a Variety of Environments of Differing Saturation Level. *In: Conservation and Management of Archaeological Sites 10*. Volume 10. P.204-222.

Hansen, G. (2005) *Bergen c 800 – c 170. The emergence of a town*. The Bryggen Papers. Main Series, 6. Bergen, Fagbokforlaget Vigmostad og Bjørke AS. 298 p.

Helle, K. (1982) *Kongsete og kjøpstad, fra opphavet til 1536*. Bergen bys historie, 1. Bergen, Universitetsforlaget. XVII, 998 p.

Helle, K. (1992) «Tidlig byutvikling i Vestnorge». In: Onsdagskvelder i Bryggens museum VII. *In: Våre første byer*. P.7-30. Bergen, Museet.

Helle, K. (1998) *Medieval fires in Bergen according to the sources*. In: The Bryggen Papers. Supplementary Series No. 6. Bergen, Fagbokforlaget Vigmostad og Bjørke AS. Etter Bergen,

Helle, K. (2005) The Emergence of the Town of Bergen in the Light of the latest Research Results. *In: Veröffentlichungen zur Geschichte der Hansestadt Lübeck. Herausgegeben vom Archive der Hansestadt. Reihe B. Band 41*. Lübeck.

Hjelle, K. L. (1986) *Paleobotanisk undersøkelse av marine sediment og avfallslag i Veisan – et bidrag til bosetningshistorien i Bergen*. Cand. scient-oppgave I spesiell botanikk. Botanisk institutt, Universitetet i Bergen.

Herteig, A. E. (1969) *Kongers havn og handels sete. Fra de arkeologiske undersøkelser på Bryggen i Bergen 1955-68*. Oslo, Aschehoug. 224 p.

Herteig, A. E. (1985a) *The Archaeological Excavations at Bryggen. The ‘German Warf’ in Bergen1955-68*. In: The Bryggen Papers. Main Series 1. Bergen. Fagbokforlaget Vigmostad og Bjørke AS.

Herteig, A. E. (1985b) Details from the medieval waterfront. In: *Conference on Waterfront Archaeology in North European Towns. No. 2.* Bergen 1983. Bergen.

Herteig, A. (1990) *The Buildings at Bryggen. Their Topographical and Chronological Development.* The Bryggen Papers. Main Series, 3. 2b. in 3. Bergen, Fagbokforlaget Vigmostad og Bjørke AS.

Herteig, A. (1991) *Trekk fra utviklingen av en feltmetodikk i norsk middelalderarkeologi.* In: Nytt fra Utgravningskontoret i Bergen (N.U.B), 1. P.7-20.

Holberg, L. (1737) *Den Berømmelige Norske Handels-stad Bergens Beskrivelse.* København.

Hollesen, J. & Matthiesen, H. (2012) *Effects of infiltrating water into organic cultural layers.* National Museum of Denmark, Conservation and Natural Sciences, Copenhagen. Report no 11031268.

Hollesen, J. & Matthiesen, H. (2014) The Influence of Soil Moisture, Temperature and Oxygen on the Oxidic Decay of Organic Archaeological Deposits. *Archaeometry*, doi: 10.1111/arcm.12094

Hommedal, A. T. (1990) Fischermaterialet: Dokumentasjonsmaterialet til Gerhard Fischer, *n: Fortidsminneforeningens årbok, 990.* P.161-186.

Hordaland fylkeskommune (2005) *Verdenskulturminnet Bryggen i Bergen. Forvaltningsplan.* 103 p.

HT = Norsk Historisk Tidsskrift. Christiania 1871-.

Høiaas, K. <http://prosjektbryggen.no/skattkammeret/spor-av-ord/>

ICOMOS Norway (2000) *Bergen Wharf (Bryggen). World Heritage Convention. Periodic state of Conservations Report 1999-2000.* 41 p.

Jennings, S. & Rogerson, A (1994) The distribution of Grimston Ware in East Anglia and beyond. In: Leah, M. 1994 [ed.]: *The late Saxon and Medieval Pottery Industry of Grimston, Norfolk: Excavations 1962-92.* East Anglia Archaeology. Report No. 64, 1994.

Jensen, J.A. (2009) *Forprosjekt for tetting av grunnvannslekkasje – Tiltaksbeskrivelse.* Rapportnummer 610706-1-2. Multiconsult AS

Jensen, J.A. & Stordal, A.D. (2004) *Miljøovervåkningsprosjekt Bugården. Bryggen i Bergen.* [in Norwegian only]

Klaassen, R. et al. (2005) *Preserving cultural heritage by preventing bacterial decay of wood in foundation piles and archaeological sites.* Wageningen. Report on EU project EVK4-CT-2001-00043.

Koren Wiberg, J.C. (1908) *Bidrag til Bergens kulturhistorie.* Det Hanseatiske Museums skrifter, 2. Bergen, Grieg. 184 p.

Koren Wiberg , J.C. (1921) *Bergensk kulturhistorie.* Det Hanseatiske Museums skrifter, 3. Bergen, Grieg. 351 p.

Koren Wiberg, J. C. (1932) *Hanseaterne og Bergen.* Bergen. Det Hanseatiske Museums skrifter, 8. Bergen, Grieg. 264 p.

Koren Wiberg, J. C. (1939) *Schøtstuene i Bergen.* Det Hanseatiske Museums skrifter, 12. Bergen, Grieg. 102 p.

Kryzwinsky, K. & Kaland, P.E. (1984) *Bergen. From farm to town.* The Bryggen Papers, Supplementary series, 1. Bergen, Fagbokforlaget Vigmostad og Bjørke AS. 100 p.

Larsen, A. J. (1997) Innskrifter – med tegn og bokstaver – Om den uovervinnelige kjærligheten. In: *Viking*, LX, Oslo, Norsk Arkeologisk Selskap. P.95-108.

Larsen, J. (2011a) <http://prosjektbryggen.no/vernehistorien/asbjorn-herteig/>

Larsen, J. (2011b) <http://prosjektbryggen.no/redningsaksjonen/vannet/oksygenfritt-vann-grunnvann/>

Larsen, J. (2013) Ikke så pen – men en utmerket kunnskapskilde. In: *Årbok for Universitetsmuseet i Bergen 2013.* P. 41-47.

Leguijt B. (2013) *Infiltrating storm water in Norway (Bryggen)*

Lidèn, H.-E. (2012) *Forfall og gjenreisning. Bryggens bevaringshistorie.* Bodoni Forlag. 137 p.

Liestøl, A. (1964) *Runer frå Bryggen. Bergen, Det midlertidige bryggemuseum.* Særtrykk av Viking. Bergen 1963. 56 p.

Liestøl, A. (1980) Bryggen i Bergen. *Norges Innskrifter med de yngre runer*, 6. 1. hefte. Kjeldeskriftsfondet, Oslo. VIII. 96 p.

Lorentzen, B. (1952) *Gård og grunn i Bergen i middelalderen.* Det Hanseatiske Museums skrifter, 16. Bergen, Grieg. 284 p.

Lunde, Ø. (1991) *Når var det egentlig det begynte?* Nytt frå Utgravningskontoret i Bergen (N.U.B.), 1. P.21-28.

Masscheleyn, P. H., Delaune, R. D. & Patrick, W. H. (1991) Effect of redox potential and pH on arsenic speciation and solubility in a contaminated soil. In: *Environmental Science and Technology*, 25. P. 1414–1419 .

Matthiesen, H. ( 2004) In situ preservation and monitoring of the cultural layers below Bryggen. In: *Safeguarding historic waterfront sites. Bryggen in Bergen as a case study.* P. 69-73. Szczecin/Bergen ,Stiftelsen Bryggen.



Matthiesen, H. (2008) Detailed chemical analysis of groundwater as a tool for monitoring urban archaeological deposits: results from Bryggen in Bergen. In: *Journal of Archaeological Science*, 35. P. 1378-1388.

Matthiesen, H. (2010a) *Preservation conditions in the area bordering the sheet piling at Bryggen, Bergen: Results from new dipwells MB15, 30, 31, 23 and MB33 installed in 2009*. Report no 11031041. Copenhagen, National Museum of Denmark, Department of Conservation.

Matthiesen, H. (2010b) *Seawater intrusion beneath the quayfront buildings of Bryggen, Bergen: Results from new dipwells MB28 and MB29, and from repeated measurements of chloride and sulphate in quayfront dipwells during 2009*. Report no 1829-17. Copenhagen, National Museum of Denmark, Department of Conservation.

Matthiesen, H. (2012) *Ground water composition at Bryggen in Bergen: Temporal and spatial variation, autumn 2011*. Report no. 11031267. Copenhagen, National Museum of Denmark, Department of Conservation.

Matthiesen, H. (2014a) Detecting and quantifying ongoing decay of organic archaeological remains - a discussion of different approaches. *Quaternary International*, doi:10.1016/j.quaint.2014.07.072

Matthiesen, H. (2014b). *Groundwater composition around the sheet piling at Bryggen in Bergen: Effects of mitigation work 2012-14*. Report no 11031562. Copenhagen, National Museum of Denmark, , Conservation and Natural Sciences.

Matthiesen, H. & Hollesen, J. (2013) *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 August 2013*. Report no 111031561. Copenhagen, National Museum of Denmark, Department of Conservation.

Matthiesen, H., Zimsen, R. V. & Mortensen, M. N. (2013) *Measurement of oxygen, nitrate, sulphate and redox potential in microcosms with waterlogged organic cultural deposits*. Report no 11074722. Copenhagen, National Museum of Denmark, Department of Conservation.

Matthiesen, H., et al. (2008) Monitoring of preservation conditions and evaluation of decay rates of urban deposits - results from the first five years of monitoring at Bryggen in Bergen. Geoarchaeological and Bioarchaeological Studies 10. *Preserving archaeological remains in situ? Proceedings of the 3rd conference*. P.163-174., Amsterdam, Institute for Geo- and Bioarchaeology.

Matthiesen, H., et al. (2014a) Preservation of the permafrozen kitchen midden at Qajaa in West Greenland under changing climate conditions. In: *Proceedings from the National Museum of Denmark*, 22. P. 383-393.

Matthiesen, H., et al. (2014b) In situ measurements of oxygen dynamics in unsaturated archaeological deposits. *Archaeometry*. doi: 10.1111/arcm.12148

Miljøverndepartementet (2005) *Leve med kulturminner*. St.meld. nr. 16 (2004-2005) Oslo, Dep. 95 p.

Miljøverndepartementet (2013) *Fremtid med fotfeste*. St.meld.nr.35 (2012-2013). Oslo, Dep. 77 p.

Mitsch, W. J. & Gosselink, J. G. (2000) *Wetlands*. First edition. 920 p. John Wiley & Sons, Inc.

Mortensen, M. N., Zimsen, R. V. & Matthiesen, H. (2013) *Oxygen and redox potential measurements related to decay of organic cultural deposits and infiltration of water - a laboratory study*. Report no 11031566. Copnehaven, National Museum of Denmark, Conservation and Natural Sciences.

Munch, P. A. (1849) *Historisk-geographisk Beskrivelse over Kongeriget Norge (Norgesveldi) i Middelalderen*. Moss, Gram. 256 p.

Myrvoll, S. (1987) Archaeological Investigations in Bergen 1980-86: Some New Aspects on the Development of the Town. In: *Norwegian Archaeological Review*. Vol.20, No.2. P.100-109. Universitetsforlaget AS, Oslo.

*Norges gamle love indtil 1387* [1846-95], 1 – 5. Christiania ; Oslo, Grøndal ; Riksarkivet 5.b

*Norges gamle love 1388-1604* [1912-1966] Annen række, 1-111. Christiania ; Oslo, Grøndahl ; Riksarkivet 4 b.

NRR = *Norske Rigs-Registranter I–XII*. Eds. C.C.A. Lange o.fl. Chra. 1861–91.

Norsk Standard (2009) *Kulturminner - Krav til miljøovervåking og -undersøkelse av kulturlag. = Requirements for environmental monitoring and investigation of cultural deposits*, NS 9451:2009. English version of the Norwegian National Standard (2012). Lysaker, Standard Norge. 25 p.

NM = *Norske Magasin 1–3*. Ed. N. Nicolaysen. Christiania. 1858–70.

Norconsult AS (2011) *Bryggen i Bergen, Grunnvannsrestaurering, Sporstoff-forsøk høsten 2011*. Rapport Oppdragsnr.: 5110650. 18 p. Statsbygg.

Riksantikvaren (2012) *Strategisk plan for forvaltning av arkeologiske kulturminner og kulturmiljøer 2011-2020. Utvidet versjon*. 22 p. Tilgjengelig online [http://brage.bibsys.no/xmlui/bitstream/handle/11250/176217/1/arkeologiske\\_kulturminner\\_strategisk\\_plan.pdf](http://brage.bibsys.no/xmlui/bitstream/handle/11250/176217/1/arkeologiske_kulturminner_strategisk_plan.pdf) ]. Read 19.03.2015

Schüring, J., et al. (2000) *Redox: Fundamentals, Processes and Applications*. P.251, Springer at [www.geochemie.uni-bremen.de/downloads/redox](http://www.geochemie.uni-bremen.de/downloads/redox)

SINTEF (2009) *Bygging på kulturlag i middelalderbyene*. Kunnskapssystemer. Byggforskserien, 721.305.

Store norske leksikon <http://snl.no/Sju-sovere>

Storm, G. (1899) De kongelige Byanlæg i Norge i Middelalderen.  
In: *Historisk Tidsskrift*, rekke 3,b.5. P.433-440

Stumm, W. & Morgan, J. J. (1996) *Aquatic chemistry. Chemical equilibria and rates in natural waters*.  
Third edition 2012. Wiley Interscience series. John Wiley & Sons.

*Sverris saga*. (1920) Ed. G. Indrebø. Kristiania 1920

Sørli, M. (ed.) (1957) *Bergens Fundas*. Bergen Historiske Forening.  
Særpublikasjon. 98 p.

Town Law (1276) = Den nyere Bylov eller Bjarkø-ret. In *NgL* 2. Christiania.

UBB diplom samlinga. = *Universitetsbiblioteket i Bergen, diplomsamlinga*.

Vorenhout, M., et al. (2004) Automated and Continuous Redox Potential Measurements in Soil. In: *Journal of Environmental Quality*. 33, P.1562–1567

Vorenhout, M., van der Geest, H. G. & Hunting, E. R. (2011) An improved datalogger and novel probes for continuous redox measurements in wetlands.  
In: *International Journal of Analytical Chemistry*., 91, P.801–810

Øye, I. (1998) Introduction. The Bryggen Papers, Supplementary Series no. 6. In: *Medieval Fires in Bergen – Revisited*. P. 9-15. Bergen, Fagbokforlaget Vigmostad og Bjørke AS. etter Bergen.



## BIOGRAPHIES

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### Ann Christensson [b.1953-d.2014]

Senior advisor Ann Christensson was an urban archaeologist at the Directorate for Cultural Heritage’s office in Bergen, Norway, for nearly 35 years. She was devoted to the safeguarding of Bryggen, especially to the issue of in-situ preservation of the archaeological deposits from a heritage management perspective. She played a key role in the inception of the deposit-monitoring programme at Bryggen in 2000, was instrumental in building and coordinating its team of experts, and continued to develop the programme and the field of environmental monitoring right up until her untimely death. At that time she was also working on the development of the Directorate for Cultural Heritage’s national policies for the management and monitoring of the archaeological heritage in situ.

### Jens Rytter [b.1963]

Jens Rytter is a senior advisor and urban archaeologist at the Directorate for Cultural Heritage’s office in Tønsberg. He has 30 years of experience from archaeological investigations and management in Scandinavia, mostly in the medieval towns of Oslo, Konghelle (nowadays Sweden), Trondheim and Tønsberg. He has since early 2000 worked closely together with Ann Christensson on issues such as in-situ preservation of archaeological deposits and sustainable methods for and environmental monitoring of the effect of building on archaeological deposits. Lately he has been working on national policies for management of post-Reformation archaeological heritage.

### Iver Schonhowd [b.1950]

Iver Schonhowd is a specialist director at the Directorate for Cultural Heritage in Norway. Trained as a conservator of archaeological artefacts, he worked for the Viking Ship Museum in Oslo for 17 years. Since joining the Directorate for Cultural Heritage in 1995 he has worked with systems for the administration of cultural heritage objects, and standardization. He is also designated as a coordinator for the directorate’s activities at the World Heritage Site Bryggen in Bergen, as well as being the leader of the Groundwater Project.

### Geir Atle Ersland [b.1957]

Geir Atle Ersland is professor of medieval history at the Department of Archaeology, History, Cultural Studies and Religion at the University of Bergen. His special fields lie within urban history, in particular medieval morphological and property history, Hanseatic history, and the historiography of Bryggen.

### Janicke Larsen [b.1971]

Janicke Larsen is Head of Exhibitions and Public Outreach at Bergen City Museum. She has more than 20 years of experience from archeological investigations, science and dissemination. She gained her doctorate in archaeology in 2007, but has mainly worked with dissemination since then. She has been responsible for, among other things, producing and updating the webpages on [prosjektbryggen.no](http://prosjektbryggen.no).

### Kevin John Tuttle [b.1962]

Kevin J. Tuttle is a hydrogeologist and has been a part-time Lecturer of Hydrogeology at the Department of Geosciences, University of Oslo. He has 20 years of practical experience, the last 18 years at Norconsult AS. For the past four years he has been head of Hydrogeology. His work experience includes urban hydrogeology, groundwater in bedrock, contaminant hydrogeology and integrated water resources. He has worked in Europe, Africa, South America and Asia.

### Rory Dunlop [b.1955]

Rory Dunlop is an urban archaeologist working at the Bergen office of the Norwegian Institute for Cultural Heritage Research (NIKU), with more than 30 years of experience of all kinds of archaeological investigations, mostly in Norway’s medieval towns of Bergen and Stavanger. He has become increasingly specialized in aspects of archaeological monitoring since 2001, particularly in connection with the work at Bryggen in Bergen, and has had overall responsibility for archaeological fieldwork and reporting pertaining to the Groundwater Project.

### Henning Matthiesen [b.1968]

Henning Matthiesen is a senior researcher at the In situ group, Conservation and Natural Sciences, National Museum of Denmark. The In situ group carries out research and consultancy on in situ preservation of archaeological remains. Matthiesen has specialized in the field of urban deposits, monitoring, and the determination of decay rates. He has been involved in the Bryggen project since 2001 and is author/co-author of more than 40 reports and publications about Bryggen.

### Jørgen Hollesen [b.1978]

Jørgen Hollesen is a senior researcher at the In situ group, Conservation and Natural Sciences, National Museum of Denmark. He has specialized in Arctic sites and in modelling the effects of climate change on the decay of organic archaeological materials. He has contributed with monitoring in the unsaturated zone at Bryggen and laboratory decay experiments.

### David Gregory [b.1967]

David Gregory is a research professor at the In situ group, Conservation and Natural Sciences, National Museum of Denmark. He has specialized in marine finds and the decay of wood. He has contributed with studies of wood from Bryggen and discussions of all data and reports.

### Michel Vorenhout [b.1974]

Michel Vorenhout is an environmental biologist, currently attached to the University of Amsterdam. He studies the variability of the redox potential in various ecosystems and develops techniques for continuous in situ measurements. He also runs his own consultancy firm (MVH Consult, Leiden, the Netherlands), mainly involved in the monitoring of archaeological sites. He works worldwide, recently with an increased focus on archaeological sites in Norway.

### Johannes de Beer [b.1971]

Johannes de Beer is a hydrogeologist and the team leader of the Groundwater and Urban Geology group at the Geological Survey of Norway. He has been involved in the Bryggen Project since 2005, carrying out research on ground-water modelling and monitoring at Bryggen as well as design of mitigation measures. In cooperation with the international multidisciplinary team of experts at Bryggen, he and his team at the Geological Survey of Norway advise the Directorate for Cultural Heritage on issues related to groundwater and preservation of archaeological heritage.

### Anna Seither [b.1986]

Anna Seither is a hydrogeologist and team member of the Groundwater and Urban Geology group at the Geological Survey of Norway. She has carried out modelling of the soil-water system at Bryggen, in order to improve understanding of the complex dynamic water movements in the archaeological deposits in the unsaturated zone.

### Floris Boogaard [b.1972]

Floris Boogaard graduated at Delft University of Technology and now works as a senior consultant at the consulting agency Tauw BV. He accepted a professorship on Spatial Transformations at Hanze University of Applied Sciences in Groningen in 2013 and is also a researcher at the TU Delft. He is one of the founders of the company INDYMO (innovative dynamic monitoring). His research and advisory fields include stormwater drainage and infiltration, innovative monitoring, design of sustainable drainage facilities and other aspects of urban water management.

### Jann Atle Jensen [b.1973]

Jann Atle Jensen is an engineer within geotechnical engineering and engineering geology. He is employed at the consulting engineering firm Multiconsult AS (formerly NOTEBY AS) as a senior advisor. He has worked continuously with subsidence measurements, soil investigations and foundation issues at the World Heritage Site Bryggen in Bergen since 2000.

### Henk Kars [b.1950]

Henk Kars was trained in Earth Sciences and earned his PhD in archaeological science at VU University, Amsterdam. He worked as head of the Science Department at the Cultural Heritage Agency of the Netherlands. In 1994 he became the first professor in Archaeometry in the Netherlands at VU University. His interest moved from the study of inorganic archaeomaterials towards remains with an organic origin. In 2002 he became the founding father of the International Symposium on Biomolecular Archaeology (ISBA). In 2000 he established the Department for Geo- and Bioarchaeology at VU University. During the last two decades his research has focused primarily on the in situ preservation of archaeological heritage. He currently holds the position of managing director of the research institute for Culture, History and Heritage (CLUE+) at VU University, an institute that brings together more than 400 researchers from different faculties.





Prosjekt  
Bryggen



United Nations  
Educational, Scientific and  
Cultural Organization



Bryggen  
inscribed on the World  
Heritage List in 1979

