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Odense – A City with Water Issues

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Abstract

In the City of Odense we have plenty of water issues, but we do not have any real “burning platforms” that can turn the focus of our politicians and other relevant people in our direction. We experience pressure from all sides: Annual mean precipitation have increased 100 mm (15\%) during the last 140 year. Extreme rains occur more often and they are becoming more intense. Surface runoff causing flooding in streams and rivers or from storm surges in the fjord area. Sometimes both occur at the same time. Rising groundwater level caused by increased recharge, diminishing needs for potable water / lesser water abstraction and by reducing the amount of excessive waters, e.g by restoring leaky sewers, which hereby stop acting as drains.

In this article, we will highlight some of the issues we encounter as seen from two different parties with their own points of view. On one side there is the municipal authority and on the other the water and wastewater company. One of the greater issues during the last several decades is the rising groundwater level beneath the city. The quality of this groundwater is also slowly deteriorating. This is of growing concern for both parties. The cause of these problems stem from many different activities that either interact or counteract each other. They can be divided into natural conditions and those caused by human activities. Examples of natural conditions are geology, geography, climate and relief difficulties. The human activities are urban development, exploitation of resources (groundwater abstraction, gravel excavation, drainage), infiltration, SUDS. One of the key elements is that the natural conditions and the human activities often act in conjunction, causing greater problems rather than less problems.

The rapid and expanding urbanization during the 20th century, have forced a deployment of well fields from early urban locations to more rural locations. This have affected the groundwater level beneath the city, so it is significantly higher today. Urbanization also affects the natural water cycle by increasing and accelerating the surface runoff, which puts further strain on the older joint sewage system under the central parts of the city, causing local flooding during heavy rains. When you consider the predicted climate changes in the future with increased intensity and volumes of water, these problems will only become worse.

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We believe that the solution to many of these problems are a greater awareness because when interfering with the natural water cycle, will cause a wide array of consequences. Therefore, it is imperative to reduce the gap between two different worlds - the
1. Introduction and background

Urban hydrology involves many different aspects. In our daily work as geologists at the municipality and the local water supply, it is rather difficult to “force” city planners, decision makers and politicians to draw attention to “the Underground”.

Regarding the translation and communication of such topics as geology, hydrogeology, geotechnology, archaeology, groundwater monitoring data and models into something suitable for city planning, decision making and policy, we are forced to have a closer look at our city-history and instead of writing yet another report, we simply have to come up with something new. For further details regarding geology, landscape and city history, turn to appendices A and B.

Reports, models, databases, time series etc. are often too complex or technical and they very often needs some form of interpretation. This constitutes a barrier of understanding and people with no or little geological knowledge will often be somewhat in the dark. During the last 2 to 3 decades, an extensive national groundwater mapping have taken place, resulting in large amounts of data, maps, reports, and groundwater models.

In an effort to raise the level of knowledge, improve the basis for planning, and support for decisionmaking, this work was done. But – and that’s a very important but – obviously, we do not think that we have succeeded in closing (or even reducing) the gap between the hydro-specialists on one side and the planners, decision makers and politicians on the other. When working with city planning, especially below the surface, there are “facts”, “challenges”, “problems” etc. that have to be taken into account. In the following, we have tried to point out what we think are important.

We have tried documenting the city growth, by digitizing old city maps of Odense from the 17th century and until today. Fig. 1 show what Odense looked like in 1839 [1]. The size at that time was around 39 acres.

The 12 maps covering the period from early 1600 and until today illustrate the development. Different in age, but with very well defined boundaries between the city and the rural areas (The City Limits). The maps should be read from left to right and from top to bottom. Examples are given in fig. 2.
Fig. 2. City Growth from the early 17th century and until today, within the Municipality of Odense (Copyright: KMS) Green dots represents well fields. [2]

Below we have shown a semi-logarithmic plot with city size and age respectively see fig. 3 [2].

Starting in the 1830’s and until to today, data follows a straight line - which means exponential growth – with a constant annual percentage around 3.2 %. Using “The Rule of 70” we can calculate a T2 (doubling-time) that equals 22 years, meaning that the city of Odense will exceed the municipal border in the year 2050 if this growth rate continues
unchanged. Many cities have growth rates around 2-4 %, some even greater. It’s not up to us to decide, whether a
doubling-time of 22 years is a problem concerning the city, but we would like to stress that such a timespan is way too
long to deal with in most ordinary municipal planning processes and much too short not to incorporate, when it comes
to physical and spatial planning of water issues.

Often we say we do, but when it comes to actual planning, we are not used to deal with time spans of one or more
generations and have long forgotten the reason for place names like “Peatmoor Rd., Bogside Street, Brooke View,
Meadow Rd. etc. when we decide where to expand or densify the city.

Besides the above described, challenges concerning city growth, we also have issues concerning climate change in
the form of increased annual precipitation, increased piezometric head and sea level rise. The surface in general is
slowly rising due to static uplift stemming from the last glaciation. Local areas is subject to subsidence due to
degradation of organic matter or consolidation of loose sediments. For more details, see Appendix C.

We will now give two different examples of conflicts between groundwater/surface water and city growth.

First example is Sanderum Toervehave (Sanderum Bog) which were formed in the proximity of a postglacial
outwash fan. The subsurface is dominated by plane bedding lithofacies. There is a small stream originating from this
area, that is surrounded by glacially disturbed till ridges. In the several small surface indentations, there are bogs that
is fed by slightly artesian springs. During the early 1800’s, the area was primarily an open landscape with meadows
and bogs and used as a training ground for the cavalry. The area have been utilized for water abstraction for more than
four centuries, starting in 1580’ies, as a source tapping springs and leading the water, untreated thru wooden pipes to
centrally placed fountains in the medieval Odense. This system was in operation from 1586 until 1850.

By the mid 1800’s the water quality was almost intolerable and the city council took steps to establish a public
water work based on British principles of groundwater filtration through sand filters. In 1853 the first real water work
in Denmark was inaugurated. The following year 1854, a severe cholera epidemic outbreak ravaged many cities in
Denmark. In Copenhagen 3809 people perished (>20%) due to this outbreak. Fortunately, because Odense had a
functioning drinking water system, no cholera related deaths occurred here. Copenhagen did not get their water work
up and running until 1857.

The increasing population demanded more water and plans for drilling new boreholes, was commenced. The first
drilled well in Sanderum Bog was ready in 1883 and have constituted the backbone of the water work since then.
The abstraction from this well field was around 1 million m3 per year at the beginning of the 20th century and with
a piezometric head at +10 m above sea level. Over time, the abstraction increased relatively slowly until the mid-1960.
From that point and the next 10-15 years, the abstraction grew exponentially to an absolute maximum of close to 7 million m³ per year, resulting in a severe drop in piezometric head to -3 m below sea level. The water quality deteriorated with an unsustainable increase in the sulphate concentration, from 20 to 170 ppm – a process often associated with groundwater mining. The deterioration in water quality led to a change in policy for a more sustainable abstraction program. At present, the abstraction is reduced and close to what was abstracted in the early 20th century resulting in a rise of the piezo metric head +10 to +12 m above sea level.

The area was publicly owned by the municipality and was slowly transformed into an urban housing area, consisting mainly of single unit estates/housing. See fig. 4, [2]. By the late sixties most of the area was covered with homes and gardens. At that time no one thought of any groundwater problems.

But everything has a price. Fig. 5, [3] show the consequences of the aforementioned city growth issue – first water mining and afterwards drowning. This unfortunate combination of a rising groundwater table and an increase of the annual mean precipitation is now causing a conflict of interest. Several drained and urbanized areas are now becoming waterlogged again and the situation is of increasing concern for the residents and constitutes a major conflict of interest.

![Abstraction vs. Groundwaterlevel](image)

Fig. 5. The abstraction of water from Sanderum Bog Well Field (data: J. Linderberg, Vandcenter Syd) [3].

In general the expansion of urban areas, causes other challenges. In some areas, the natural infiltration have been drastically reduced, due to the vast areas with impermeable surfaces. In other areas, the infiltration increases due to local residential handling of rain and surface water thru private infiltration systems. These systems are promoted by the municipality and the sewerage company and are often financially supported.

The early sewage systems were established around 125 years ago and they were all common sewage systems for both precipitation, surface runoff and raw sewage. Common systems constitutes more than half of the sewerage systems in the city. Expanding these systems to accommodate future heavy rains/climate change is both very expensive and sometimes an almost impossible task. Within the city more than one billion Euro have been invested in huge sewage pipes for delaying or storing storm water during extreme rains, in order to meet the EU-legislation by hindering/decreasing the amount of raw sewage water from overrunning into the Odense River and Odense Fjord.

As another example, we have Skibhusvej and Vinkaelderrenden. Today this is a fully built up area with one to three story housing. The development of this area, started during the 1920 - 1940’ies. The landscape is a flat top till surface where a postglacial melt water stream has cut a narrow valley and where a natural draining stream dewaters from the
south east and towards the west. The bottom of the stream is approximately 4.5 m above sea level and the surrounding plateau is 12.5 – 15 m above sea level.

The valley floor is covered with wetlands, postglacial peat bogs and small ponds. In the 1940’s this natural stream also transported sewage and the residents living with the stream in their backyard applied the municipality to convert the stream into a covered/piped system. The cost was divided equally between the parties. Later in the 1970’ies this area became popular with further urban development. This have put a massive strain on the sewage system and since it is a joint sewerage system, all water is pumped from the pumping station close to the harbor and eastwards towards the treatment plant.

During large rain events, the system is overflowing, creating flooding of rainwater and raw sewage on terrain and in basements of the low-lying residential areas. It is difficult and very costly to change the system in this neighborhood, because over time, this natural draining stream have been converted into a sewage system.

The massive costs of these infrastructural changes have provoked a growing interest in trying to establish local systems for artificially/naturally enhanced infiltration of rainwater. This, again, - is putting further strain on the water level and saturation beneath the city.

That was two examples of how urban development and groundwater levels and drainage are in conflict.

Many of these problems were caused by urbanizing areas that are prone to flooding. These problems will only be amplified by the predicted climate change in the form of increased precipitation, rise in sea level and near-surface groundwater etc.

New large scale suburban infrastructural projects like tunnels and underground parking facilities is also challenging the groundwater saturation issue and may ultimately alter the nature of groundwater flow patterns etc.

We can see many legitimate activities in the city that counteracts each other. E.g reducing water abstraction contributes to a rise in the groundwater table, challenging subsurface infrastructures and low-lying areas. The work of reducing excessive waters tends, to reinforce the problems related to near surface groundwater.

Due to the above-mentioned topics, we face a large array of issues in our daily work: some occur suddenly and they are actually more often caused by the lack of information/communication or knowledge at the planning stage. This is mainly due to poor sharing of knowledge and wrong decisions etc. It is actually quite rare that we lack the necessary data and/or information. Some problems starts very small and may escalate over longer periods of time, where no one really notices it or feels the responsibility to deal with it, until suddenly the problem is eminent and “someone, has to do something, really quickly!”

2. Possible management options.

One way of solving a recurring flood risk was implemented in a suburban area southwest Odense. This was originally open farmland with small bogs and draining ditches. In mid-seventies the area was turned into a residential area with many detached or semidetached houses. The bogs were drained and the open ditches were turned into a piped system. Since the early development of this area, additional housing have been built and the piped system was inadequate to cope with more and more precipitation draining from each lot (roof runoff, parking areas and tiled areas of each house).

Some repeated massive rain events over just a short time span caused flooding downstream in an area where there used to be a boggy low-lying area. Several estates were flooded causing major damage. Insurance companies were reluctant to reinsure the properties because of these repetitive events. The properties would therefore become almost impossible to sell. To solve this problem by installing a larger pipe system would be almost impossible, both financially and technically.

The solution to this problem turned out to be both ingenious and quite inexpensive compared to any traditional solution. It was simply proposed by some of the affected owners of flooded property to buy them out at a fair price (market value without the flooding!) and demolish the homes and turn the area into a retention basin. See fig. 6 [4]. The area is now a popular local park and recreational area that doubles as a retention basin whenever this is needed. This was one of the first times in Denmark where we created a sustainable and durable solution and where property damage is something of the past. A real “never again flooding” solution.
The sewage system receives and transports a lot of excessive water from surface runoff. In some areas close to half the volume treated is excessive water. Old leaky sewage pipes acts involuntarily as drains for groundwater. To reduce the amount of water entering the treatment facilities, a plan for refitting and relining old sewage pipes have been going on for years and the hope is that it will eventually reduce the draining of groundwater. This will in turn cause more problems for those estates that have benefitted from this involuntarily drainage.

VCS Denmark is the sole operator on sewage transport and treatment. It is therefore of great interest to minimize excessive surface and groundwater from entering the sewage system. The municipality is also advocating the possibility to handle the main part of the rainwater from rooftops/impermeable surfaces, locally, by trying to make the public willing to establish seepage systems, e.g. soak-ways in their own back yard. Those who do, will get an substantial economical compensation on the properties connection fee. This is of course a major challenge because of the great geological heterogeneity and the water tables close proximity to the surface. Soak ways (gabions) in till-clays are not necessarily very efficient to cope with in the current or future heavy rain events.

Those who abstract water, are by law, responsible for damage on buildings, water bodies and environment caused by the lowering of the water table. This is not the case if it is the other way around. Water abstracters are usually not liable for damages due to positive changes of groundwater level, if residents have been duly informed about the planned changes in abstraction patterns. Rising levels of the groundwater table to previous (natural!) levels is therefore a matter of each landowner.

All in all, we are facing a wide array of issues that either interact or counteracts each other. One solution for an isolated issue may end up causing severe interference on other problems. Interfering with the natural water cycle in order to solve a specific problem often entails new problems. Reducing abstraction causes water levels to rise. Relining sewage pipes reduces drainage. Massive urbanization increases surface runoff. All of these elements causes problems for landowners one way or the other. The future climate with increased rainfall, and frequent high intensity rain events will only add to the conflict by adding further strain on all systems.

We believe that it is imperative for all key players (urban planners, developers, water and sewage operators, politicians and underground specialists) to acknowledge the water cycle and the natural drainage system that has shaped the landscape. It is absolutely necessary, to reserve space for drainage in urban development. It is also vital that we do smarter planning and not utilize low-lying areas to place critical infrastructure (subway stations, hospitals, emergency response units, and other sensitive utilization).
There are many cities were planning and development have been done without thought of what the future environment regarding surface and groundwater changes will bring of challenges, when trying to cope with excess water regardless of type. Mankind have become so confident that we can build anywhere and hope that nature will be status quo as today. This is often not the case!

The importance of the subsurface beneath our cities is often under-recognized and overlooked. We are all part of a natural cycle of rain and runoff and several problems occur when we interfere in this cycle, and the issues mentioned above all in all, are very familiar examples of urbanization problems in most big cities. We think that more clever ways of addressing these issues to each other, planners, decision makers and politicians, for example could be new smart ways of visualization.

We do not just want another advanced 3D geological or hydrogeological model, but a functional project management tool that – with a city or topographical model on top, in an easy and intuitive way can handle, combine and most importantly visualize all sorts of underground information - from basic geology, geotechnical, archaeological, aquifer specific water levels, protection/abstraction zones for potable water, hot zones for energy storage, pollution ……etc, to all sorts of buried suburban infrastructure.

We hope this can act as a strong tool to reduce the gap between two different worlds - the underground specialists on one side and the planners, decision makers and politicians on the other and we believe this will constitute a great informative breakthrough and facilitate evaluation, processing and planning above and below the surface.

3. Conclusive remarks:

According to the UN, 66 % of the world population will live in cities the year 2050 [13]. This escalating urbanization introduces a huge amount of issues. In this article, we have addressed three main topics - city growth, interference in the natural water cycle and climate change.

The handling of these topics in a smart way, in order to minimize some of the negative consequences, demands a close collaboration between all involved parties.

We have seen several examples where city planning, implemented with little regard to the natural hydrology, have caused multilevel problems. Some of these problems can been avoided by minimizing the gap between the underground specialists on one side and the planners, decision makers and politicians on the other. One effective way is close cooperation and knowledge sharing on many levels, early in the process.
Appendix A. Geology and landscape.

The landscape of Funen where formed by several ice age transgressions that have deposited tills, sands and gravels. The thickness of the glacial deposits varies from 10 - 150 meters. The stratigraphy mainly consists of three sand/gravel-aquifers separated by clayey till-deposits. The lower sand-aquifer is more scarcely distributed than the middle and top aquifers, due to erosion and deformation by ice-tectonics during the activity by younger glaciations. The glacial deposits rests on deposits of Cenozoic age. They consist of chalk, clay, limestone, and marl and the latter form the lowermost groundwater aquifer of Funen.

There are several buried valleys, which have eroded into the underlying deposits, sometimes even as deep as the pre-quaternary deposits. They are filled with sand and gravel deposits, interbedded with tills. Faulting and folding of these strata have affected some of the major visible terrain-forms. E.g. deep fault lines in the Cenozoic coincides with the location of the present valley for Odense River, which flows from the southwest towards the inlet, to the north east. See Fig. A1.

The landscape around Odense is dominated by a moraine plain to the south and east, with some larger areas of alluvial deposits to the east. In the western part, there is a transition zone to a dead-ice landscape caused by an ice sheet that ceased to move and melted in situ. This area is a hummocky terrain covered by glacio-fluvial sediments and ablation tills. North east of the city there is a shallow estuary. Several areas around the fjord is reclaimed land. Much of the cultivated landscape is artificially drained to accommodate farming.

The river and its smaller tributaries have eroded some more or less distinct valleys into the surface. In the urban area of Odense, the river results in a marked valley through the central part of the city. Adjacent to these river valleys, are bogs and marshy land, that were drained and later urbanized. Organic rich deposits stemming from paleo-bogs can be found along the river valleys. The difference in elevation between the valley-floor and the higher ground are no more than 10-20 meters.

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Fig. A1. The landforms of today, brown: Weichsel-moraines, yellow: diluvial sediments, green: esker, blue: marine foreland [6] [7].

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Fig. A2: Hill shade map showing the topography of the northern part of the municipality. [2]

The elevation of the old central parts of Odense City is around 10 meters above sea level and the harbour area is approximately 2 meters above sea level, see fig. A2 [2]. In the southern part, the terrain rises gently to a level of 20-25 meter above sea level. The low-lying areas especially the inner parts of the Odense Fjord with much reclaimed land are vulnerable to sea-level rise caused by storm floods or more long-term events as climate changes. The isostatic uplift that have progressed since the last glaciation period shows an uplift rate of 1 mm/year in the Odense area. This cannot eliminate the observed and ongoing sea-level rise of around 2 mm/year (data from 1971-2010) but maybe it can alleviate the negative effects for many years to come.

The city have challenges in ways of handling the growing amount of surface water that we have experienced, in the last decade. The worry is, that these challenges will be even greater in the future.

Since 1974 when L. Mertz [8] performed a geotechnical mapping of selected cities (incl. Odense) there have been no systematic mapping of the subsurface in urban areas in Denmark. In recent years focus on urban geology have become more important due to e.g climate change and urbanization, and in 2012 the municipality of Odense, VCS and GEUS initiated a collaborative project to develop a comprehensive 3D geological model of the subsurface of Odense. Most of the previous mentioned suburban infrastructures with trenches and fill material, and selected geotechnical and archaeologica information, were incorporated in this model. This model with both geology and anthropocene elements can act as a very useful tool for management and administration of the urban water cycle. A synthesis report is available at Mielby, et. al. [9].
Appendix B: City History, with focus on city growth, suburban infrastructure and water supply.

Odense is one of the oldest cities in Denmark. Our ancestors started settling here during the Stone Age, more than 4000 years ago. Probably starting with small settlements along the Odense River and Fiord area and later around the Viking Ring Fortress called Nonnebakken. In 1850, it was a small borough of 11,000 people, covering only 2.5 km², it has increased to more than 175,000 inhabitants at present (2017), covering an area of almost 100 km² corresponding to ⅓ of the size of the present Municipality of Odense with a total population of more than 200,000. See Fig. B1. [2]

The “The Odense Canal” that connects the old harbour area in the central part of the city with the Odense Fjord (inlet) area north of the city, influences the infrastructure of Odense. The Canal is 5 km long 7½ m deep and “man-made”, excavated with shovels and wheelbarrows from 1796 to 1806. Upon completion, the Canal provided passage for goods that could be loaded/unloaded from ships in the middle of Odense leading to city growth and increasing prosperity. The industrialization got another boost by the completion of the railway in 1865 and this led to a associated growth of city north, east and west of the city centre. See fig. B2.

The second industrialization period from 1950-70 led to the creation of new industrial settlements outside the city and in the small neighbouring municipalities, most of them being a part of our municipality today. The university of Odense (today: The University of Southern Denmark) was established in 1965 and from 1975 – 1990 a new part of town (Odense South) have developed between the city center and the bypassing highway. From 1990 and until today new homes were built in the city center and many townhouses and block of flats have popped up in the suburbs.

One of the main goals for the city council is that at least 70% of all urban development shall happen within the current city limit through urban densification and renewal. This is also the reason why only a few urban growth areas have been chosen to be put in the suburbs.

Low-rise buildings dominate the City of Odense - “the city of residential neighborhoods”. The old parts of the city center are typically 3-4 floors but the new district plans, among other things, now accept taller buildings in the harbour area and also in the central parts of town. One of the goals of the city is to create a great big city center and to reinforce the impression of transforming Odense from a large city to a metropolis.

In Odense, there are approximately 114,000 buildings of different kinds. Odense is one of a very few municipalities, having made a digital connection between the geographical location of a building and a Building/Residential database. By combining these data (GIS), we know that a little more than 60,500 of these are actual houses for living, production, storage, offices and buildings for sports and cultural purposes – 52,100 are
located within the city limit and the rest (8,400) are situated in the rural areas. More than 1/3 (21,600) of these buildings have a basement and 92% of these are situated within the city limit. In other words Odense may be flat – seen from the surface but it contains many subsurface structures– why that’s interesting, we’ll come back to later.

In addition to the above-mentioned basements, other examples of suburban infrastructure or suburban impact beneath/within the city of Odense are:

- Pipes and pipelines:
  We have more than 2100 km of sewerage pipes, ranging from very small and up to 300 centimetres in diameter together with 1700 pumping stations placed underground. There are more than 2000 km of district heating network to supply central heating to more than 85,000 households, and 7,000 companies and institutions. A network of pipes for natural gas with diameters ranging 90 down to 2 centimeters in diameter. The gas is transmitted from gas fields in the North Sea to a distribution network for end users in Odense.

  Furthermore we have more than 1500 km pipelines for potable water. Our 13 waterworks have approximately 100 active abstraction wells and within the municipality we have an additional 233 individual household wells/dug wells and 195 wells different industrial purposes. In addition to that we have knowledge of more than 3200 investigation wells/boreholes made for other purposes like geotechnical, (hydro) geological, archaeological, dewatering etc. Average and maximum depths respectively, are around 18 m and 200 m.

  Until present day we only have 210 horizontal Ground Source Heating/cooling installations (closed loop systems), but there are plans for a huge Aquifer Thermal Energy Storage (ATES) installation in the central part of the city and there are aspirations for more systems in the near future. Last but not least, we have a huge network electric cables for power supply and optical fibres for communication.

  Of course leaky pipes and pipes acting as drains are hydrologically important, but in many cases also the backfill in the pipe-trenches plays an important role in controlling the flow regime.

- Miscellaneous:
  We have roughly 600 underground storage tanks. The majority range between 6000-100,000 liters and in most cases, they are used for the storage of oil/gas. Other examples of artificial underground structures are parking garages, subsurface wastewater and stormwater basins of varying sizes. Also drains and gabions for the extraction or infiltration of surface or rainwater.

- Areas - above/below ground:
  Quarrying areas, especially plenty of old gravel deposits within the city limit of today have been abandoned and often refilled with all sorts of waste materials. The land use on top of these refilled areas are in most cases green areas or city parks, but some with residential housing. We also have a multitude of contaminated sites: “The sins of the past” also includes present and past industrial sites with possible polluting activities scattered all over the municipality, which have led to pollution of more than 1100 sites and in several cases also pollution of the groundwater. Some sites even affect the indoor climate of housing above the site rendering them less inhabitable.

- The life and death of water works and well fields:
  Of special interest in this infrastructure context is the history of the waterworks. Over time the number of water works have changed drastically from 1 thru 45 and back to the present 15. In general, most waterworks were started during the period from 1920 up until the early 1970’s. Historically, many of the water works in Denmark, are privately operated on a cooperative basis with voluntary management. The general increase in complexity due to legislation, refurbishment, maintenance and public demand have forced many of these voluntary cooperatives to give up independency and merge with adjacent waterworks.

  The larger publicly owned water companies have taken over both facilities and network. Many of the small production facilities were deemed unprofitable, and have been closed and dismantled. There is a national trend of general consolidation in the water business so that these small water works will become even scarcer in the future.
As mentioned above many of the previous water works in Odense have disappeared, see Fig. B3. [2]. Some due to pollution, deterioration of natural water quality, the need of major technical refurbishment or other activities. It is important to notice that not even one of these water works were built inside the city limit, when they started. They were all established outside the city of Odense, in rural areas.

Fig. B3. Water Works or Well Fields: Green spots indicate the active ones and red the abandoned [2]

The water work infrastructure of Odense has changed dramatically over the years. The peak of abstraction within the urban areas was 1974, with more than 11 million m³/year. In 2016, the total abstraction within the city limit have been reduced to the same amount as in 1911! See fig. B4, [3] Also, several large industrial facilities have stopped their own abstraction during the same period. From 1947 the location of abstraction started moving outside the city into rural areas both south and south west of Odense. Today more than 65% of the abstraction is now placed outside the municipality of Odense.

Fig. B4. The sum of abstraction within the city limits and the rural areas including outside the municipality.[3]
Appendix C: Inevitable factors

C1: Precipitation:

In Denmark, the annual precipitation varies significantly from place to place and from year to year. In general the average annual precipitation (from 1961-90) is 712 mm and this has increased by approximately 100 mm since systematic measurements were introduced in 1874. See Fig. B5.[10]

![Figure B5: Annual Mean. Precipitation for selected Danish Meteorological Stations, from 1874 - today. The blue curve shows 9 years Gaussian Filtered Values][10]

Lessons learned until now, and future estimates suggest that precipitation in wintertime will increase, summer periods will become drier and that severe rain events will become even more extreme. It’s very difficult to predict the impact of precipitation-related climate changes on the shallow ground water reservoirs, but the majority of climate models indicates a rise in piezometric heads - in sandy more than clayey areas.

C2: Sea level changes and isostatic uplift

For more than 100 years the observed sea level around Denmark (except Northern Jutland) has risen. Differences in the observed sea water levels are due primarily to isostatic uplift. A process that started when the last glaciation period (The Weichselian) ended some 11,500 years ago and the uplift of the former ice-covered land masses began. The iso-curve running through the Odense area, shows an annual uplift of 1 mm/year. However this cannot fully eliminate the observed sea level rise of approx. 2 mm/year (1971-2010), but it can, in some way, alleviate the negative effects for years to come. See Fig. B6 [11].

When compensated for this, all monitoring stations with long time series show that the water level has gone up by an average of 1.7-2.2(±0.3) mm annually. Data from Denmark is very similar to the global average [12].

When the mean sea level increases, the maximum water level in the event of a storm surge, it can be expected to be even greater. The best future-estimate of the water level e.g in the case of a 50-year event will therefore be: the water level in the case of a 50-year event today plus the expected sea level rise compensated for isostatic uplift, waves and wind. Other local conditions and e.g. tidal effects, may also affect future storm-surge water levels.
C 3: Subsidence:

In addition to the basic uplift showed on the map above, we see local examples of even greater uplift or extreme subsidence in the range of 10 mm/year. Strong subsidence can be related to, the geological conditions – e.g. the consolidation of sediments or water abstraction/dewatering.

Generally, the subsurface of Odense is geotechnical stable, but deposits rich in organic material, may pose a problem for construction, if they are de-watered, during or after construction work. In some parts of the city centre, the foundations of older buildings probably consists of wooden piles or grillage, which both tends to decompose, if the groundwater table is lowered, so they no longer are submerged in water.

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