Alternative Drainage Schemes for Reduction of Inflow/Infiltration - Prediction and Follow-Up of Effects with the Aid of an Integrated Sewer/Aquifer Model

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Introduction

Human use of land always affects the hydrological balance, and the use of land for urban development has pronounced effects on the local hydrology. The urban storm drainage and sewer systems interact with the local groundwater in a complicated manner. In many cases most of the rain falling over houses and gardens is drained by foundation drains and leakage to the sewers, often with substantially increased inflow/infiltration after a rainstorm as a result (Bäckman, 1985).

Practical experience show that conventional measures only on the sewer network itself, often have a low effect on the inflow/infiltration, especially the groundwater infiltration, and often at a high cost. To decrease these flow components more untraditional methods, like new drainage schemes, cutting the natural ground water stream, must be taken into consideration. Now a number of new technical and legislative questions arise: At what depth and horizontal location should the new drains be built to become the most efficient, and what effects can be expected on the flow? Will a changed groundwater drainage negatively affect house foundations, sensitive vegetation, and maybe existing groundwater abstraction wells? Are there any practical design aspects that must be considered to insure a safe and long lasting operation?

The answers to many of these questions demand a thorough geohydrological understanding of the drainage processes of the catchment studied. Generally, computer models have proven to be valuable to increase the understanding of involved processes, and even more important, to predict the effects of alternative measures. Few models have however shown their capability to describe the interaction between sewer network hydraulics and the surrounding geohydrological processes at an appropriate scale.

Conceptual models are today widely used, and with success, for the modelling of these processes and their effect on the sewerage system. The conceptual model MOUSE NAM has in Sweden been applied in hundreds of catchments to model hydrological processes affecting the infiltration/inflow components in sewer networks (Gustafsson, 1995). However, one of the disadvantages with these conceptual models, is their inability to fully consider existing overall knowledge of the catchment. Neither do they explain the physical underlying reasons for certain results. This means that the effects from future measures in the urban environment, i.e. alternative drainage schemes etc., only to a limited extent, if at all, can be described with a conceptual model. But still, to analyse the effects of alternative measures is often one of the main reasons for applying models. Modelling tools, able to describe the geohydrological processes in a more physical and distributed manner, are therefore needed to obtain more knowledge and understanding for these processes.

On the market today, physically based geohydrological model concepts already exist. One of these more advanced models is the MIKE SHE model (Abbot, 1986), developed at DHI Water and Environment. MIKE SHE has up to now been widely applied on traditional surface and groundwater problems in water resources areas. In particular, MIKE SHE has been shown to be a very capable tool when the effect of human interference is to be assessed.

Innovative Pilot Project Introduced Physically Based Modelling into the Urban Aquatic Environment

To examine to what extent MIKE SHE is practically applicable in urban modelling areas, a research project was carried out with support from the Swedish Water and Waste Water Works association. The overall goal was to test if it is possible to describe the surrounding geohydrological processes and their interaction with the sewer network, similar to the way dynamic pipe flow modelling can give a detailed description of the hydraulics.

The modelling methodology was applied in a small village outside the city of Kristianstad, Sweden. The project was presented by Gustafsson et al (1996). The application showed that the model was fully capable to describe the relevant processes, and indicated that it not only could be calibrated but also used for predictions of future changes in the combined aquifer/sewer system.

One of the interesting scenarios studied was what would happen with the groundwater table if the sewer system as a whole was fully tightened, or similar, if it did not exist, i.e. natural conditions. Luckily, the relining measures previously taken was not successful, because the model predicted a number of small lakes (dark blue) in the middle of the village, see Figure 1 (the houses in the village are included as an information layer).

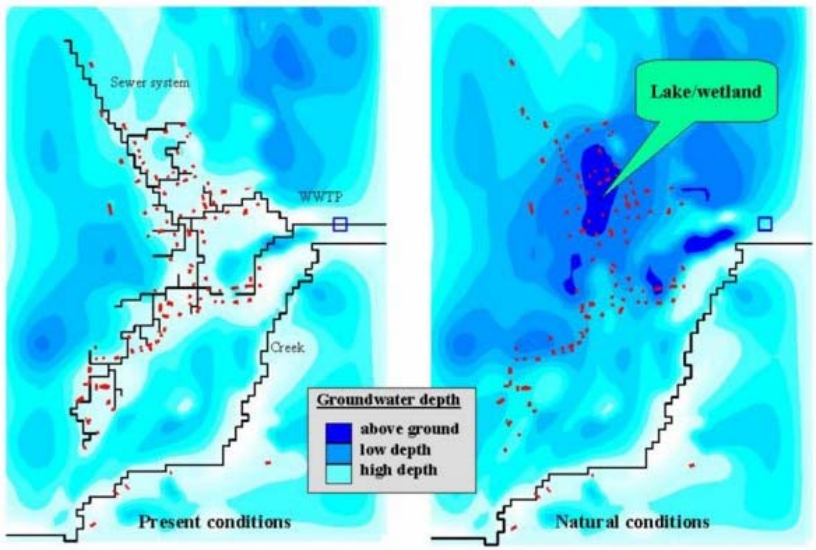

Figure 1

Nice to look at, but not for the people living in the bottom. At the same time, simulated groundwater depths for present conditions show expressively how the sewer network keeps the groundwater table at a low level along the sewers and properties.

The model was used to design a new drainage scheme in order to decrease the extremely high inflow to the small treatment plant, caused by groundwater infiltration into the sewer network. The reduction of sewer infiltration by the new drains was predicted to at least 75%. During the fall of 1996, the new drains were constructed and taken into operation. Now, a few years later, flow measurements show that the design and construction was successful, with a reduction of the inflow to the plant even exceeding the predictions. The measured inflow for a year before the new drains (1988), and after construction (1997), is shown in Figure 2. Also, the pump flow from the drains are shown. Observe the rapid increase of the inflow to the plant during the short stop of the drain pump early 1997.

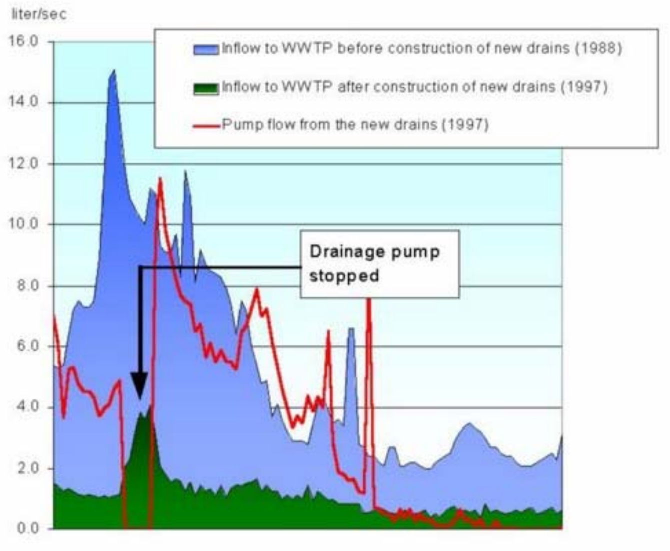

Figure 2

Further development and validation of the modelling and solution approach

With these terrific results in mind, a new research project, supported by the Swedish Water and Waste Water Works association, was started a few years ago with the aim to dig more deeply into this subject. More specifically the project includes:

- development of a dynamic link between the MOUSE system (for sewer hydraulics) and the MIKE SHE system (for catchment hydrology and groundwater hydraulics), aiming at a fully integrated tool.
- thorough follow-up of the Vittskövle project, both from an operational and hydrological perspective;
- two more case studies in two other sewer systems with similar problems and approach as in Vittskövle, but different system characteristics;
- general discussion on legislative and practical design aspects, based on feed-back from both involved case studies and other catchments in Sweden where similar methods have been applied;

The following sections gives a glance from the two new case studies as well as description of the major principles behind the integrated modelling package.

The Integrated Sewer-Aquifer Model

MIKE SHE

MIKE SHE is a deterministic, distributed and physically based modelling system for simulation of hydrological processes in the land phase of the hydrological cycle. The model is applicable to a wide range of water resources and environmental problems related to surface water and groundwater systems and the dynamic interaction between these. The modelling package comprises a number of pre- and postprocessors to facilitate the input of data and the analysis of simulation results, among others: space interpolation routines; graphical editing; and plots of the variations in space and time of any variable, as well as animation tools.

MIKE SHE simulates the variations in hydraulic heads, flows and water storage on the ground surface, in rivers and in the unsaturated and saturated subsurface zones. The spatial variation of meteorological input data and catchment characteristics are represented in a network of grid squares. Within every grid square the soil profile is divided into a series of vertical layers. The model structure is illustrated in Figure 3.

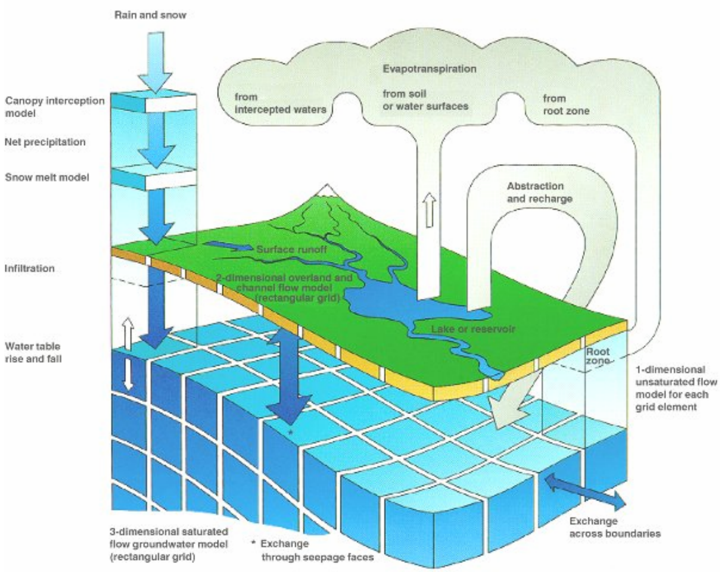

Figure 3

In addition to the water movement module, the modelling system includes modules for spreading and degradation of pollutants, mapping of capture zones, wetland ecology, etc. For more complex river hydraulics, the river modelling package MIKE11 can be used fully integrated with MIKE SHE.

MOUSE

MOUSE is the well known world wide spread modelling package for urban drainage and sewer systems (Lindberg, et al 1989). In addition to the fully hydrodynamic pipe flow model and conceptual surface runoff and inflow/infiltration modelling capabilities, the system includes modules for transport of pollutants and sediments, as well as off-line and on-line modelling of real time control.

The link between MOUSE and MIKE SHE

MOUSE and MIKE SHE are coupled at three physical elements:

- The two way interaction between pipes and the aquifer. The interaction equation is based on the temporal and spatial variation of the water pressure in the pipes and the surrounding aquifer, the pipe surface to which the ground water is exposed to (or the waste water is exposed to if exfiltration), and a leakage coefficient. The equation is:

$$\mathbf{Q_{in} = (H_{gw} - H_{sewer}) \times P_{sewer} \times C.}$$

- The one way transport of flow from foundation drains, service lines and smaller pipe systems (not described as pipes in MOUSE) into a certain manhole in the MOUSE sewer network. The drainage equation is based on the ground water level, the drainage level (typical foundation level or similar), and a drainage coefficient. The equation is:

$$\mathbf{Q_{dr} = (H_{gw} - H_{dr}) \times A_{grid} \times C_{dr}.}$$

- The abortion of areas in MIKE SHE being impermeable and consequently described with the surface runoff model inside MOUSE. The areas aborted in MIKE SHE might be a fraction of a full grid square.

In all other respects, the two models are built and executed as if they were two singular models. The principle is illustrated in Figure 4.

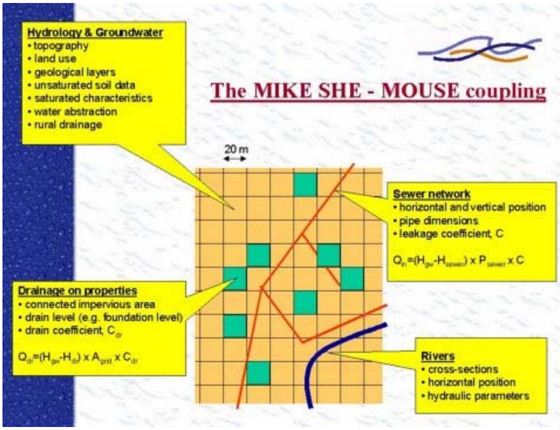

Figure 4

Setting up the model for a typical urban application

Both of the model components are distributed and physically based. This means that most of the input data are of geographic, geometric or geophysical type. In addition the meteorological conditions, as well as some specific semi-physical information are given to the models. The input data typically includes the following:

- Topography
- Land use and crop characteristics, e.g. differing between forest, agricultural areas, meadow, urbanised
- Base map with houses, properties, roads, etc
- Impermeable surfaces and runoff characteristics
- Geometry for rivers and creeks
- Geometry for the sewer network
- Foundation levels (if foundation drains are to be encountered)
- Geological information including hydraulic characteristics
- Information about water abstraction wells
- Time series of daily precipitation (and temperature if snow melting is to be encountered)
- Monthly typical potential evaporation

Although MIKE SHE has a built in mini-GIS-system, the interpretation and checking of input data as well as analyses of output data, are more feasible to carry out with a full GIS-system. Therefore, MIKE SHE can be coupled to the ArcView GIS-system with a number of dedicated applications. One of these is the ArcView/Geoeditor, where 3D geological models can be built based on geological field data. Figure 5 illustrates the principles of the application, showing how geological layers can be interpreted and defined based on bore hole data.

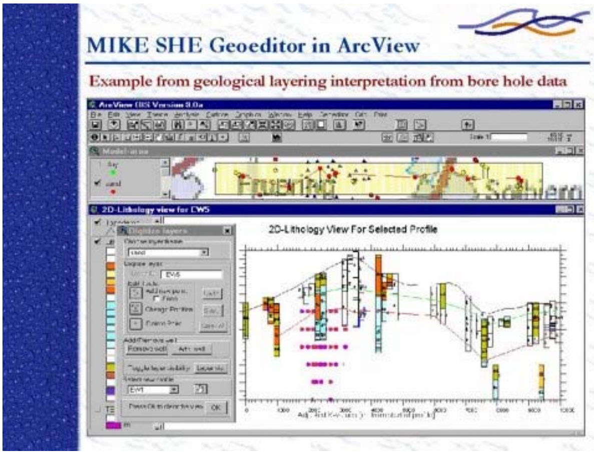

Figure 5

Parts of the interaction between the two models are based on a conceptualisation of the very complex physical behaviour in the soil volume represented by the lumped grid square of typically 20 by 20 m. However, as long as exact physical information about the condition of pipes, service lines and foundation drains is not available, which it very seldom is, a more physical approach on this micro scale is not applicable. But, the conceptualisation requires a calibration procedure to obtain reliable drainage coefficients and leakage coefficients. The applications so far indicate however, that the drainage coefficient typically can be set quite high if foundation drains are present, and the leakage coefficient has a correlation with the condition of the pipe system (e.g. indicated from TV-inspections).

In addition to the typical input data above, the calibration procedure assumes the following data to be available:

- Groundwater level observations
- Observed inflow/infiltration at all available sites
- Any information concerning condition of pipes, foundation drains, historically wet areas, etc.

The number of groundwater level observations and their location in the area to be studied must be based on local experience. In the applications so far, with a catchment size between 200 and 500 ha, 6 to 12 observation sites have been used.

When discussing sewer flow observation sites, it is crucial to cover both the temporal and spatial variation. In all of the applications, the most downstream observation site has covered between 5 and 10 years of daily flow data (typically at the waste water treatment plant or a pump station). In addition, distributed single time observations of flow at a large number different sites in the sewer network has been used in order to obtain a reliable distribution of the drainage and leakage coefficients in different sub-areas of the sewer network. These single time observations, typically carried out during night when the foul sewage flow is low or even zero, should if possible be carried out at different hydrological situations. Finally, some real time flow monitors ensures that the fast response flow components also are covered, although this is not in focus when groundwater infiltration to sewers is the subject.

Finally, all other relevant information that can help when trying to understand these complex interactions, are of interest, e.g. TV-inspection protocols, observations from the catchment inhabitants, etc.

Application in the City of Halmstad, Sweden

The catchment and problem characteristics

The City of Halmstad in Sweden holds around 70 000 inhabitants, and is located on the west coast with the river Nissan passing through - Figure 6. The area studied, called Nyatorp, is a part of the city centre, mostly with family houses with basements, with a size of approximately 500 ha. The geology is mainly sandy soils of around 3 to 4 m with underlying silt and clay. The topography is low and flat, with typically very high groundwater levels in the area. The sewer system is of an old combined type from the 30´s and the 40´s, with very poor condition. All together, this means a sewer system with a large amount of groundwater infiltration as a result. Therefor, the City has decided to rehabilitate the whole pipe system in the area, including the water pipe system.

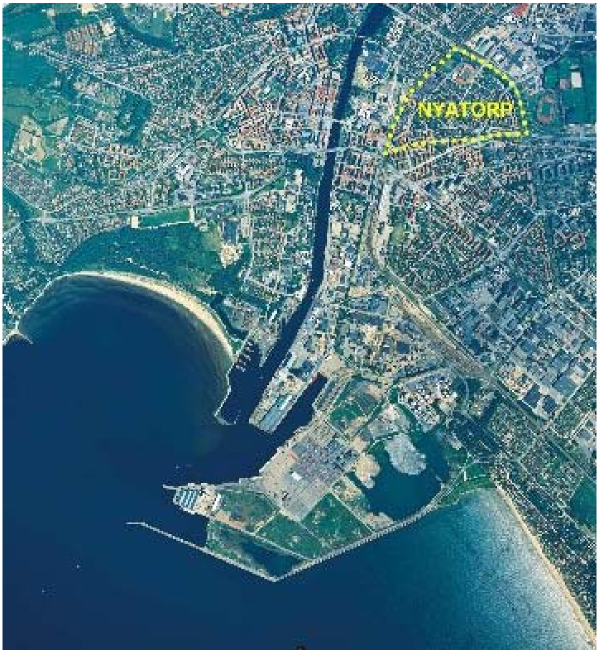

Figure 6

In an earlier rehabilitated area in the city, problems arose when the old leaking sewers where replaced with new sewers, with moisture and flooding problems in house foundations and basements as a result. The characteristics of the Nyatorp area indicates that such problems are likely also in this area, if the geohydrological conditions and proper measures are not carefully analysed. Naturally, the possibility to forecast the effects from a rehabilitation and possible additional measures was crucial for the City, and the decision to use the integrated MOUSE-MIKE SHE system was taken.

The solution

Due to the leaking sewers, typically much deeper then the foundations, at present only few houses are surrounded with high groundwater levels. The old system works as a well functioning drainage system for the area. This is illustrated in Figure 7, showing the relation between the simulated groundwater levels and the house foundation levels.

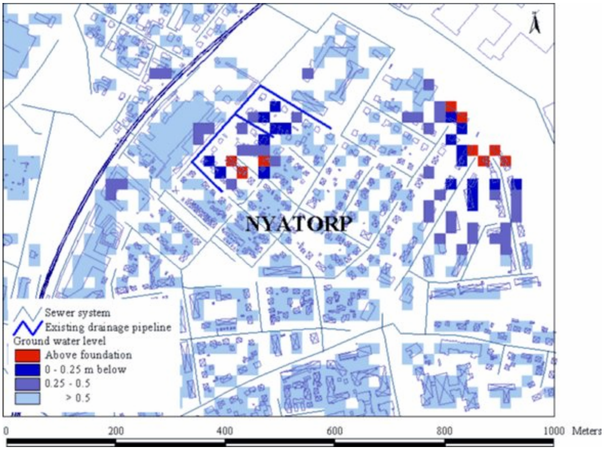

Figure 7

After a complete rehabilitation of the sewerage system, the corresponding picture is predicted to be as shown in Figure 8 - not too good!

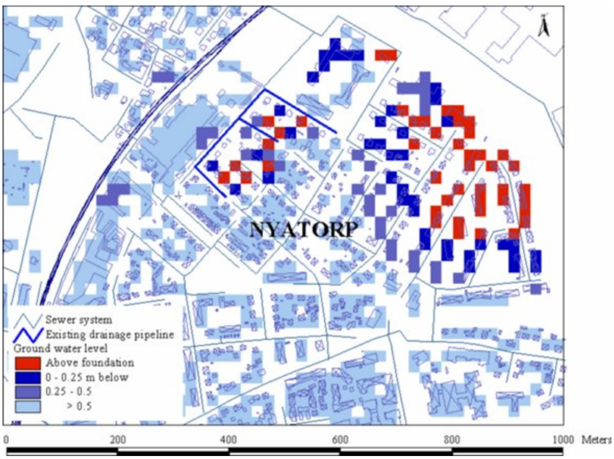

Figure 8

A number of alternative solutions were tested in the model, and finally a feasible drainage scheme was found, that would lower the groundwater levels to the present conditions at the least. The scheme, as well as the predicted results, are shown in Figure 9 (the new drains are marked with red lines) - not too bad!

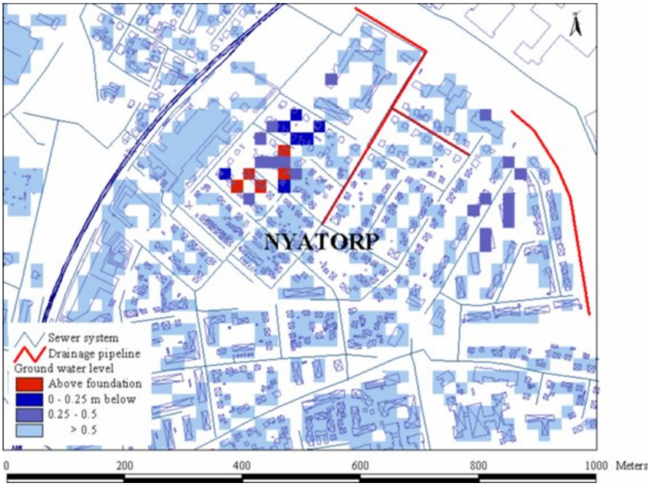

Figure 9

These results were taken seriously, and the construction work of the solution has now started. A snapshot of the field work in the pipe-ditch is shown in Figure 10, also pointing out the drainage pipe in the bottom of the pipe-ditch. The real results will be thoroughly followed through flow observations in the sewer network, as well as groundwater level observations in the area the coming years.

Figure 10

Application in the village Köpinge, Sweden

The catchment and problem characteristics

Köpinge is a village south of the city of Kristianstad. The village holds a population of around 1000. The river Vramsan is cutting quite deep through the village, and the surrounding topography is rather flat, though inclining towards the river on both sides. Many of the houses are without basements, but in some parts basements are common. The upper geology is similar to the case in Halmstad, i.e. mostly sand with some underlying clay lenses. The deeper geology is however completely different, with a large artesian sandstone and limestone aquifer, and a quite thick tilt layer on top. The groundwater pressure in the deep aquifer is typically controlled by the precipitation volume of the last couple of years, not the situation of the actual year. The sewer system in the centre and in the south are of older combined type, while the northern parts has a separate system. The inflow to the local treatment plant exceeds the capacity over long periods due to a large amount of groundwater infiltration in the system, and with the very sensitive Vramsan being the recipient, the need to decrease these problems are obvious. The groundwater infiltration to the plant, i.e. excluding sewerage foul flow, is shown in Figure 11, both observed and simulated. The sewerage foul flow is in average only around 30% out of the total inflow volume, and during some months less then 15%.

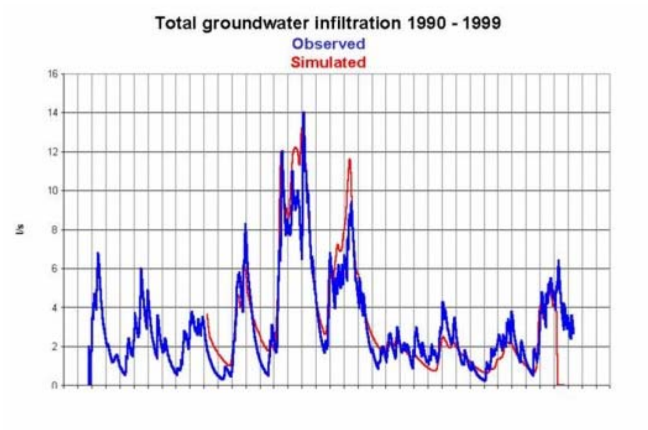

Figure 11

Through the previous project carried out by the city of Kristianstad in Vittskövle (see above), with excellent results from both the analyses and solution methods, the step to continue with Köpinge in the same manner was very little.

The solution

Based on the main groundwater flow directions for the present system, and the detailed information concerning major sewer infiltration areas, a large number of potential new drainage schemes were tested. The final solution that was chosen is shown in Figure 12, and includes two new drainage lines in the northern and the southern parts.

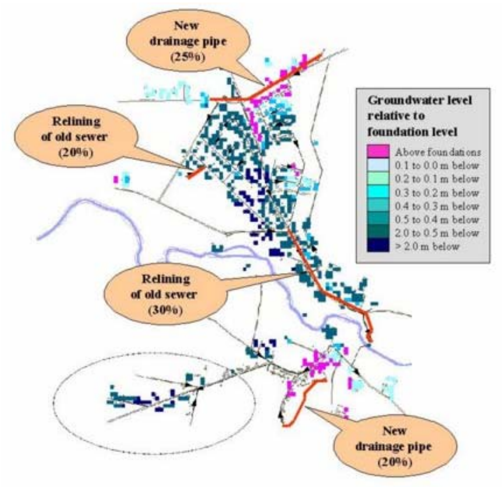

Figure 12

In addition, the solution scheme also includes relining of old sewers in two other branches where house foundations are above the typical yearly maximum groundwater levels, thus avoiding problems with the foundations in future. The different measures in the scheme is marked with red lines in the figure, and the percentages written at the proposed measures, indicate the fraction of observed groundwater infiltration out of the total observed at the plant. The predicted effects with this alleviation scheme indicate a very high reduction of the inflow to the plant, shown in Figure 13.

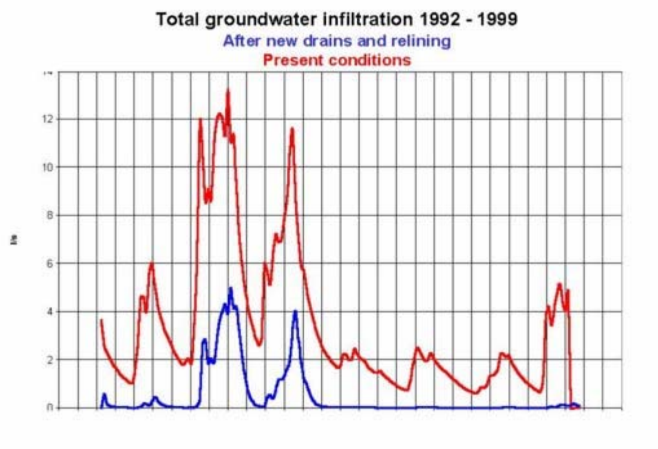

Figure 13

Observe the smaller reduction of the flow during year 1994 and 1995. During these years, the groundwater pressure in the deep aquifer is extremely high, with a high upward flux as a result. According to the model, this would activate leakage in the south-west branch (marked with a dotted circle in figure 11), where normally the groundwater levels are lower then the sewer system, thus causing leakage where the proposed solution is not relieving the sewer system. It is however assumed that these conditions are very extreme, and will only happen a few times over a decade, and the decision was to leave this as it is. The detailed design will now continue, and construction work of the measures is supposed to be carried out early 2001.

Conclusions

The method of analysing the problems

The use of advanced modelling tools has once again proven to be a very efficient way of how to increase the knowledge of the behaviour of complex problems. The integrated MOUSE-MIKE SHE model has now been used on three different kinds of catchments, with different characteristics, and has in all cases proven to be capable to describe the interaction between sewer systems and surrounding groundwater systems.

Compared with more simple conceptual models, this distributed and physically based modelling system provides the possibility to analyse the effects from future changes in the geohydrological system. This is crucial before a decision can be taken that otherwise might change the groundwater pattern completely, and in the worst case create flooding or settled foundations. However, a distributed physically based model like MIKE SHE also demands much higher geographical resolution of the input, increasing the time for setting up the model, but of course, consequently, permitting higher geographical resolution of the output.

The water modelling software puzzle is here and the integration goes on

With the recently developed Integrated Catchment Simulator - ICS (Clifforde, Tomicic, and Mark, 1999), integrated planning, management and operation of waste water systems has been turned into a feasible approach, where the software pieces comprises MOUSE for sewers, MIKE11 (1D flow) or MIKE21 (2D flow) for receiving water bodies, and STOAT for waste water treatment plants. The new coupling between MOUSE and MIKE SHE, has brought a new piece into the water modelling software puzzle - Figure 14 - and the integration goes on!

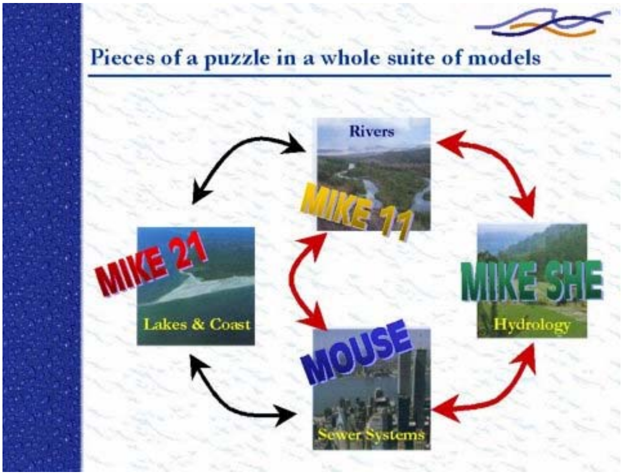

Figure 14

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