Bathing water forecasts for the general public - coupling urban, riverine and coastal operational modeling of bacteria

Dick Karlsson and Olof Liungman

DHI Sweden, Lilla Bommen 1, Göteborg, Sweden, e-mails: dick.karlsson@dhi.se and olof.liungman@dhi.se

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Abstract
The west coast of Sweden is well-known for its beautiful and numerous beaches. Tourism is of great importance to the local economy, and thus high-quality bathing water is paramount. Also, European and Swedish legislation requires municipalities to oversee the bathing water quality through continuous monitoring for various types of fecal bacteria.

Three municipalities contracted DHI to set up a bathing water forecasting system, available to the general public via the internet. This system combines several different models providing operational forecasts of the concentration of fecal bacteria. A high-resolution 3-D hydrodynamic model (MIKE 3 FM) of the coastal areas provides forecasts of currents, temperature, etc. This model is forced by a large-scale operational model of the seas surrounding Denmark and Sweden and atmospheric forecasts provided by a third-party supplier. The transport and decay due to mortality of fecal bacteria are modeled using a separate module (MIKE ECO Lab), which is forced by urban and rural sources of bacteria. Urban sources are calculated from forecasts of rain whereas river runoff is modeled using MIKE 11. The model outputs are post-processed and presented on a webpage using Google Maps technology in an easy to grasp format.

In this presentation the different parts of the system will be described and results will be presented.

INTRODUCTION

The west coast of Sweden is well-known for its beautiful and numerous beaches. Tourism is of great importance to the local economy, and thus high-quality bathing water is paramount. Also, European and Swedish legislation requires municipalities to oversee the bathing water quality through continuous monitoring for various types of fecal bacteria.

Three municipalities – Varberg, Halmstad and Laholm – contracted DHI to set up a bathing water forecasting system, available as a service to the general public via the internet. The purpose of the system is to provide the general public with more detailed information than the at best bi-weekly sampling of bacteria whose results are only available in retrospect. Hopefully, this will show the public that the water quality in general is good at the beaches covered by the system but should also help prospective bathers avoid instances with poorer water quality and thus reduce the risk of bathers contracting illnesses due to fecal bacteria. In addition, the system provides forecasts of weather and water temperature for the convenience of those pondering a day on the beach. Furthermore, the system can be used to identify the sources of and reasons for high bacteria concentrations to enable efficient mitigation and planning. Finally, the system may hopefully also lead to greater understanding of the processes involved, both among decision makers and the general public.

The forecasting system should combine high accuracy with easy to grasp presentations of the results. This means that a fairly complex and advanced system is required that both forecasts the sources of bacteria and how the released bacteria spread and decay in the coastal water. At the same time, the results of these complex models must be distilled to something that is useful to the general public.

In this paper the different parts of the system will be described and results will be presented.

THE FORECASTING MODEL SYSTEM

The bathing water forecasting system consists of a number of different models coupled together (DHI Bathing Water Homepage; Karlsson et al, 2009). The core consists of a high-resolution 3-D hydrodynamic model (MIKE 3 FM) that provides forecasts of currents, temperature, etc. in the coastal waters. This model covers the coastal areas of the three municipalities on the west coast of Sweden, from Kungsbacka in the north to Helsingsborg in the south, as shown in Figure 1. Near the shore and in particular close to beaches the resolution is highly enhanced to accurately describe the hydrodynamic conditions and thus the spreading of bacteria. Because this local model has a long open boundary towards the central parts of the Kattegatt – the sea between Sweden and Denmark – it must in turn be forced by a large-scale operational oceanographic model of the seas surrounding Denmark and Sweden (see Figure 2). On its remaining boundaries the local model is forced by meteorological forecasts – with 0.1 degrees resolution – provided by a third-party supplier (STORM Weather Center) and computed local river runoff.

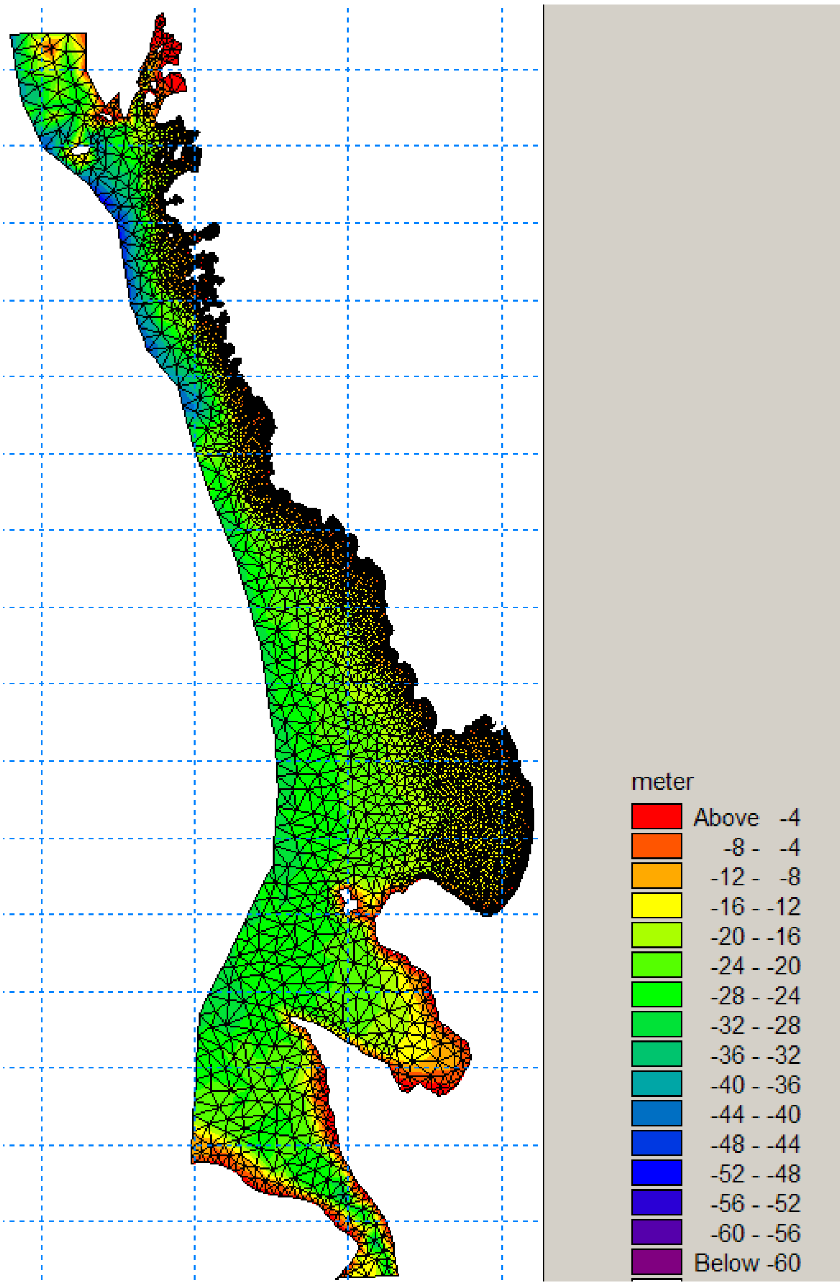

Figure 1: The model mesh of the MIKE 3 FM model, with the Swedish west coast to the east and the Kattegatt to the west. The color legend shows the model depths.

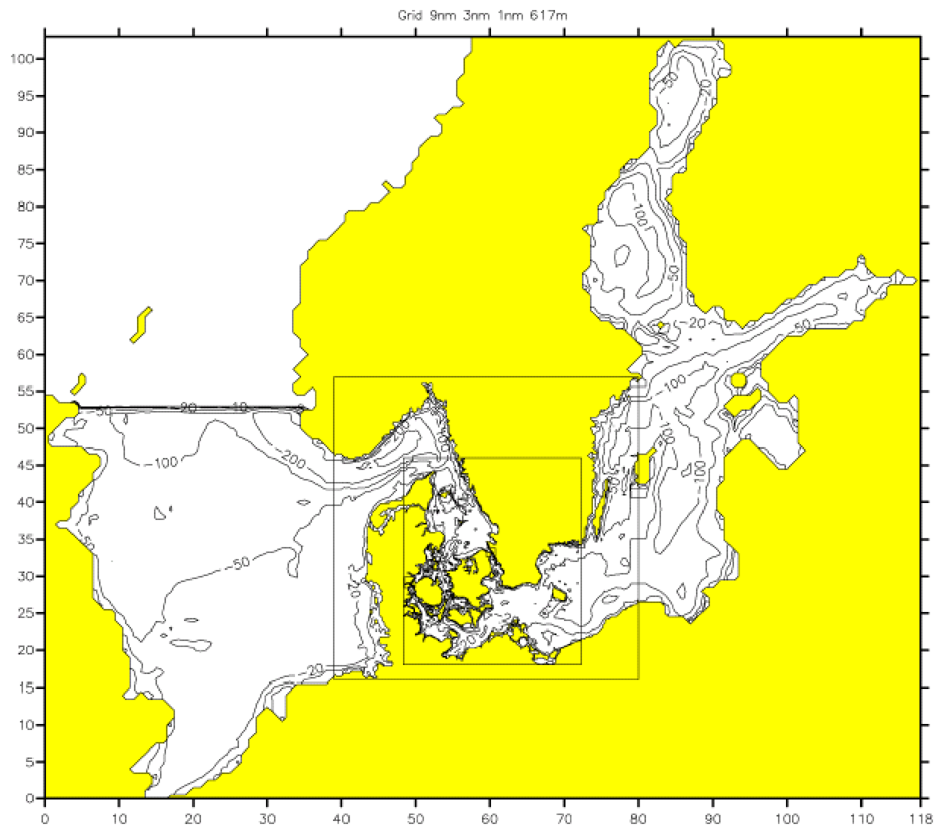

Figure 2: Model domains of the three nested levels of the operational Water Forecast model for the seas around Denmark and Sweden.

The transport and decay due to mortality of fecal bacteria are modeled using a separate module (MIKE ECO Lab). This add-on module is directly coupled to the MIKE 3 FM hydrodynamic model, utilizing the currents, mixing and water properties calculated by the hydrodynamic model to compute the fate of the fecal bacteria. The decay of the fecal bacteria is a function of the salinity, temperature and solar radiation at different depths. Thus, the MIKE ECO Lab bacteria model is forced by the hydrodynamic model, meteorology and the urban and rural sources of bacteria.

There are three sources of fresh water and associated bacteria content in the model system: sewage treatment plants, storm water discharges, overflows from combined collection system networks and natural watercourses. The latter three are dependent on the precipitation and must thus be forecasted using different models.

For each storm water discharge the flow is calculated using an empirical model based on forecasted precipitation and the area of the associated paved surfaces. Overflows are also calculated using an empirical model which takes as input the wastewater flow, the network's downstream capacity, associated paved surface area and forecasted precipitation. The flows in natural watercourses are calculated using the conceptual rainfall-runoff model MIKE NAM. Observed flows have been used to calibrate the rainfall-runoff model for the runoff basins that discharge into the coastal area in question.

The models described above are coupled to each other and also communicate with a database containing forecasted forcing data (input) as well as with the post-processing and presentation system (output). This will be further described below.

SOURCES OF BACTERIA

For each fresh water source in the model a constant concentration of fecal indicator bacteria – *E. coli* and intestinal *Enterococci* – is assigned (cfu/ 100 ml). In total there are more than 80 sources of fecal bacteria, divided among the following main categories:

- Sewage treatment plants
- Natural watercourses
- Storm water discharges
- Overflows from collection systems

In Figure 3 the locations of the four categories of bacterial sources are indicated.

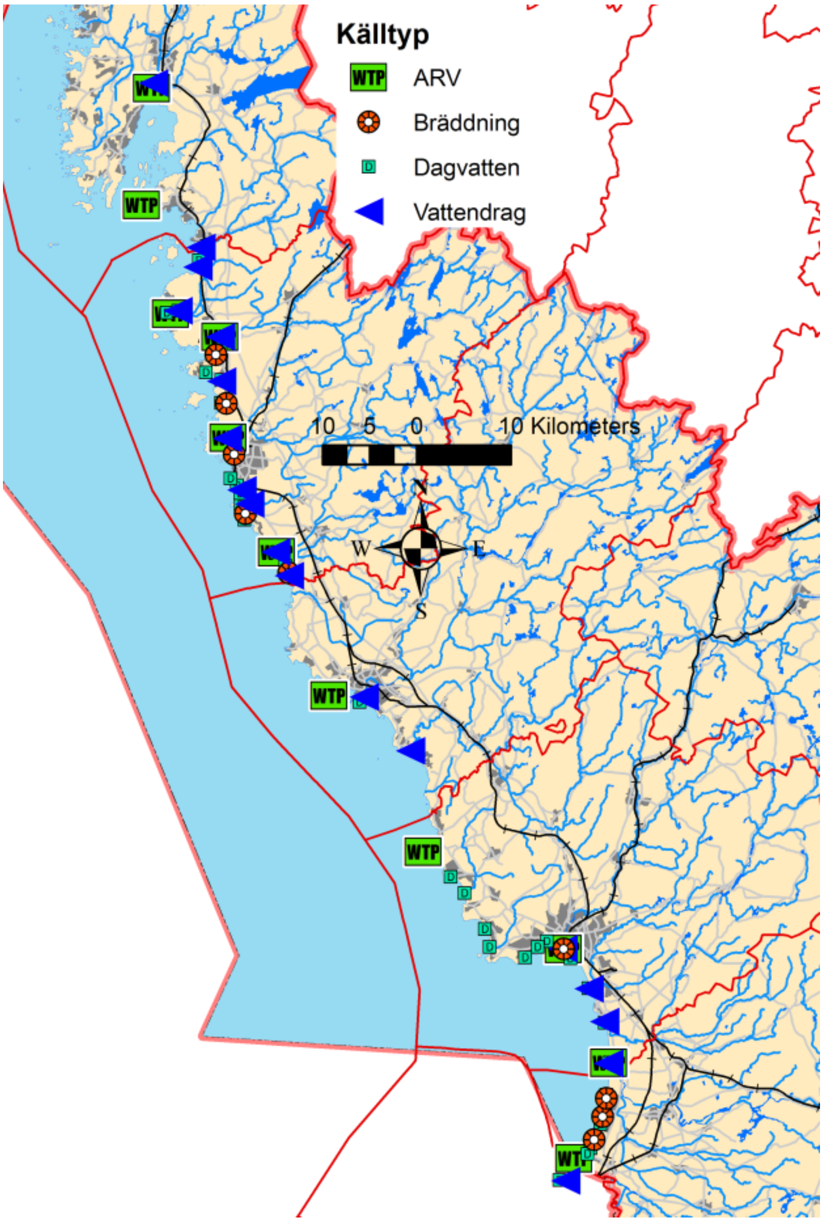

Figure 3: Sources of bacteria included in the model system: sewage treatment plants (green markers labeled "WTP"), overflows (red circles), storm water discharges (light green squares) and natural watercourses (blue triangular arrows). For clarity all sources are not shown.

There are eleven sewage treatment plants with a combined mean discharge of approximately 1.5 m^3/s. The discharge flows are constant in the model and set to the observed summer mean flow in each plant. In total there are over 40 discharges of storm water in the model associated with a surface area of 2500 ha. As for overflows, there are a few emergency overflows which have not been included due to insufficient data, leaving 12 overflows in the model. Finally, there are approximately 20 discharges of natural watercourses, i.e. rivers and streams.

There is very little data on bacterial concentrations. Those that exist have been combined with general recommendations based on different studies to determine reasonable estimates for each source included in the model.

THE PRESENTATION SYSTEM

The coupled MIKE 3 FM/MIKE ECO Lab model produces time and space varying fields of bacterial concentration. An example is shown for a small part of the model domain in Figure 4. From these the bacterial concentrations are extracted at representative points for each of the 22 beaches included in the model. For example, Figure 5 shows the beaches within the municipality of Varberg for which forecasts are produced. The concentrations are then compared to the regulated threshold values for "unsuitable bathing water quality" according to the EU Bathing Water Directive, namely 300 cfu/100 ml for intestinal *Enterococci* and 1000 cfu/100 ml for *E. coli*. These bacteria are usually not in themselves a danger to human health but serve as indicators for those pathogens that are.

If both bacterial concentrations are always below their respective threshold levels during a given day a green flag is shown for that particular beach and day. If either of the two bacterial concentrations exceeds their respective threshold levels at any time during one day of the current forecast a red flag is shown for that day.

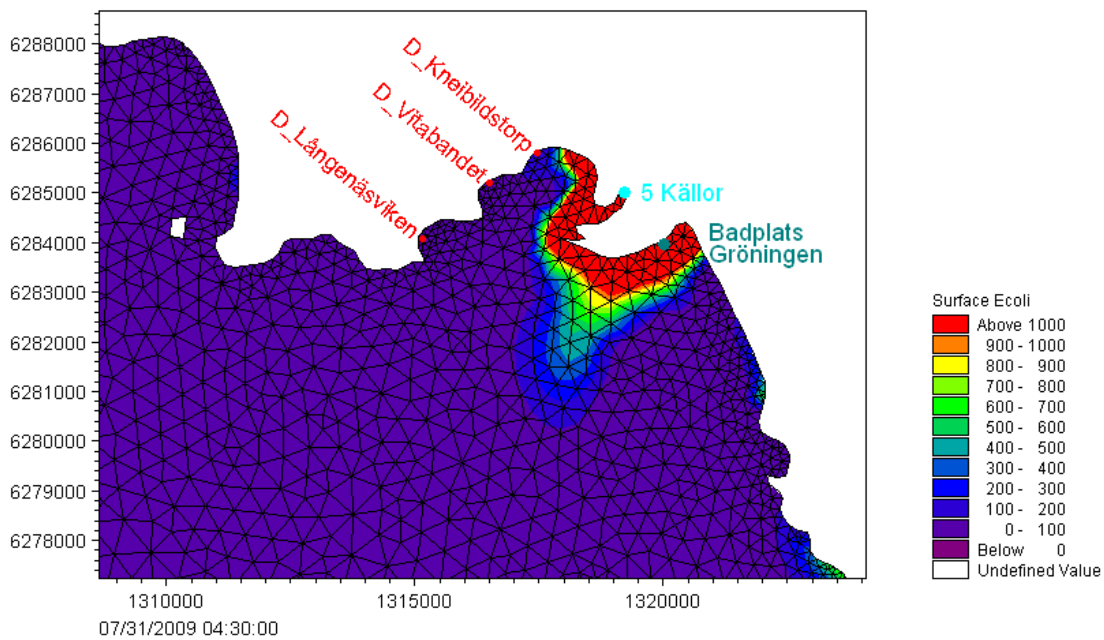

Figure 4: An example of model results showing the distribution of E. coli at a given instant of time originating from a local source in the vicinity of the beach Gröningen. Red color signifies "unsuitable bathing water quality". Note the large spatial variations and strong gradients.

Figure 5: Beaches within the municipality of Varberg that are included in the forecasting system.

These indicators are presented via a web-interface using DHI's Dashboard Manager and Google Maps. The user first reaches a start page (see Figure 6) where a specific beach may be selected using drop-down menus or by clicking on the beach's flag in the map. This brings up a separate pop-up window which for each of the four days in the forecast displays the computed bathing water quality as colored flags together with forecasts of weather, precipitation, air and sea temperature, wind and current (Figure 7).

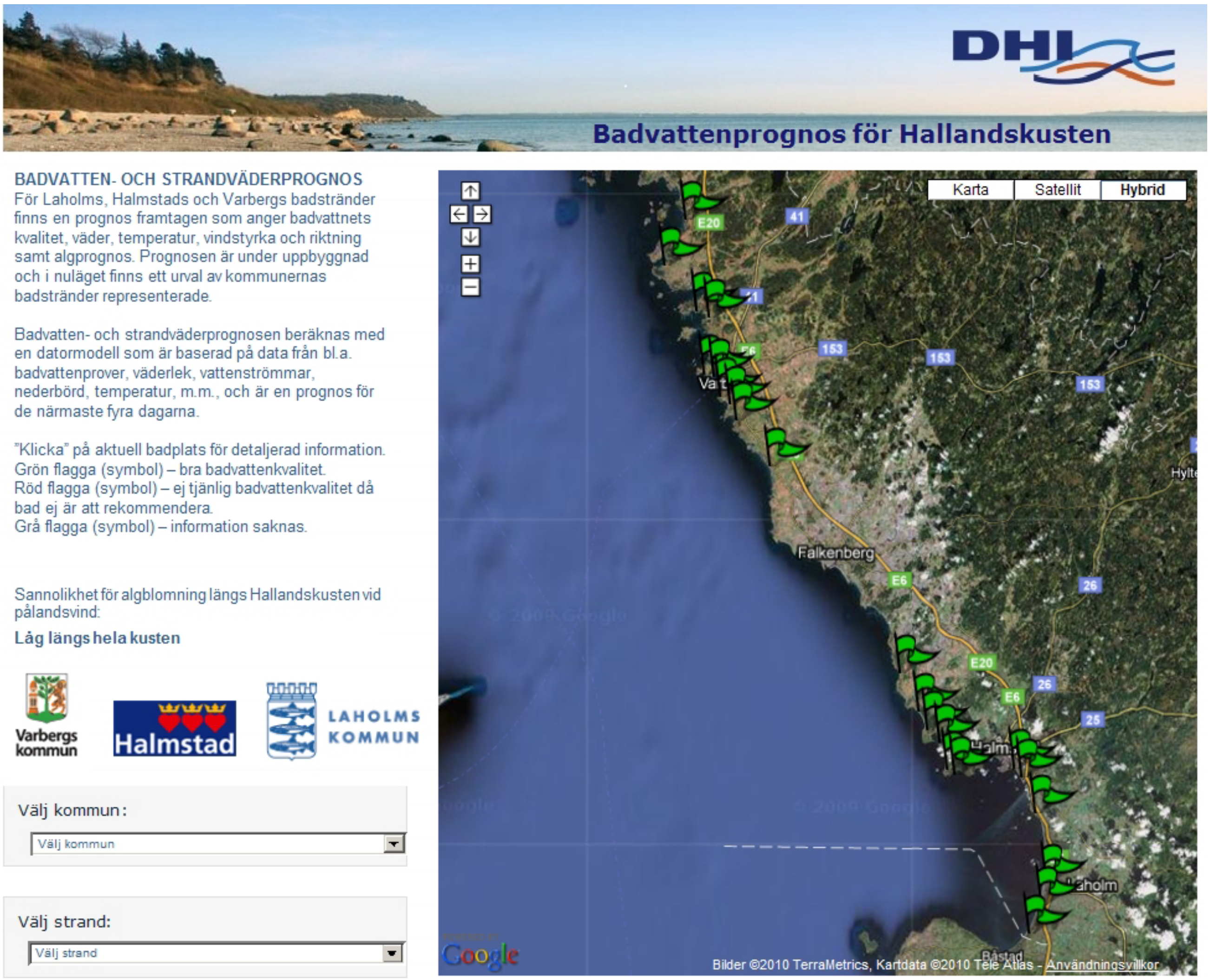

Figure 6: The bathing water forecast homepage showing an overview of the location of the beaches (http://hallandskusten.badvatten.se/).

In addition, on the first page the likelihood of algal blooms (*Nodularia Spumigena*) during onshore winds is presented as text, e.g., "low", "elevated" and "high", including a comment on whether it applies to the whole coastal area, the southern part of the coast or the northern part.

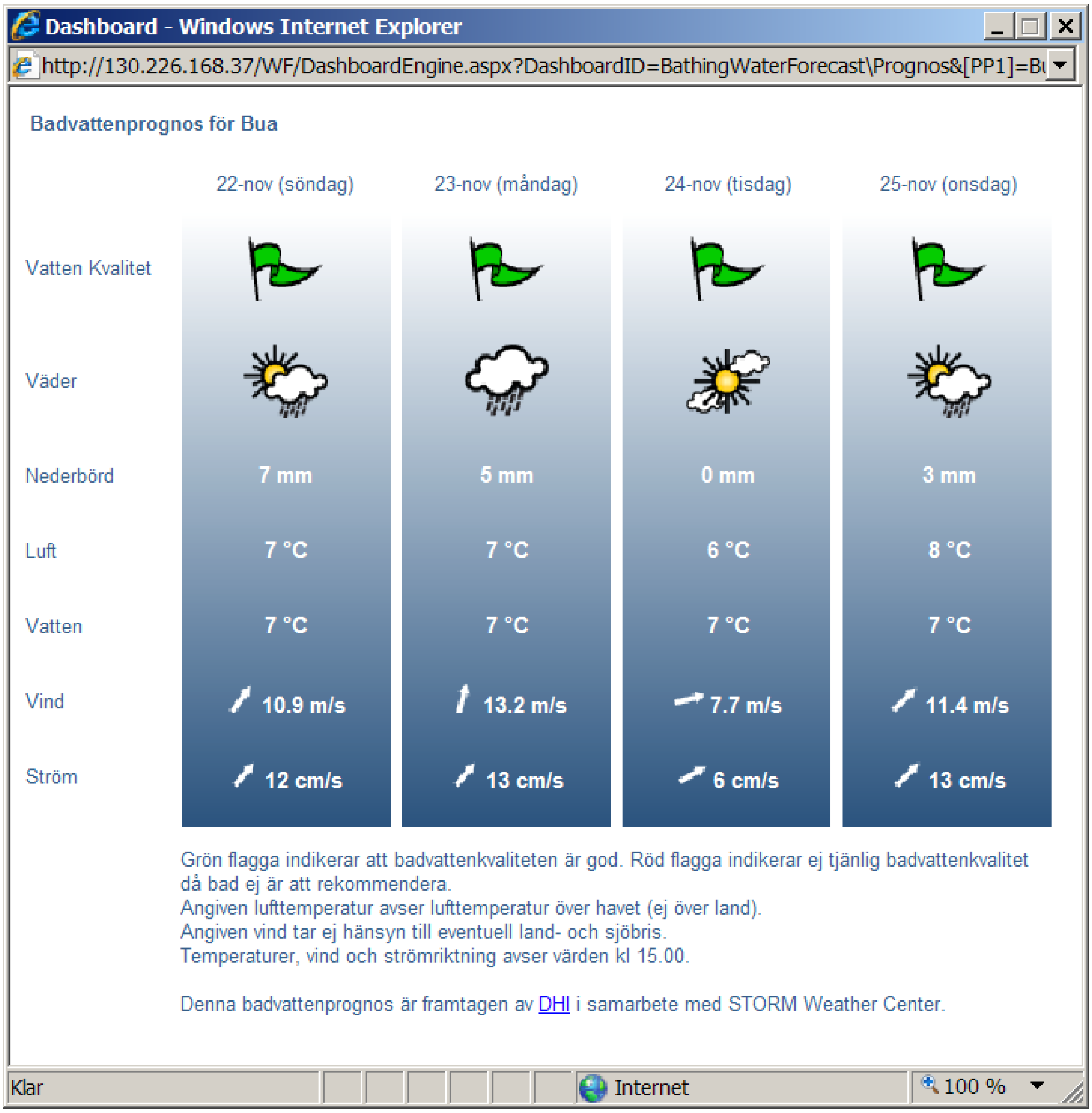

Figure 7: The forecast pop-up window for a selected beach.

DATA AND OBSERVATIONS

All the models used in the forecasting system have been calibrated to the extent that observational data has been available.

The NAM model has been calibrated using observed discharges in the watercourses for the years 2006-2007. It should be noted that rainfall data is only available at three stations, one in each municipality. This means that all the precipitation-dependent sources – watercourses, storm water and overflows – have been calibrated using observed rainfall from a single point only. Furthermore, for periods when data is missing from one station rainfall data from the nearest of the other two has been used.

The hydrodynamic model has been calibrated and validated using monthly observed salinity and temperature from a small number of offshore stations (Figure 8).

Finally, observed sea temperature and bacteria concentrations at the beaches in question are available for the summer season, though only in single points and with low temporal resolution.

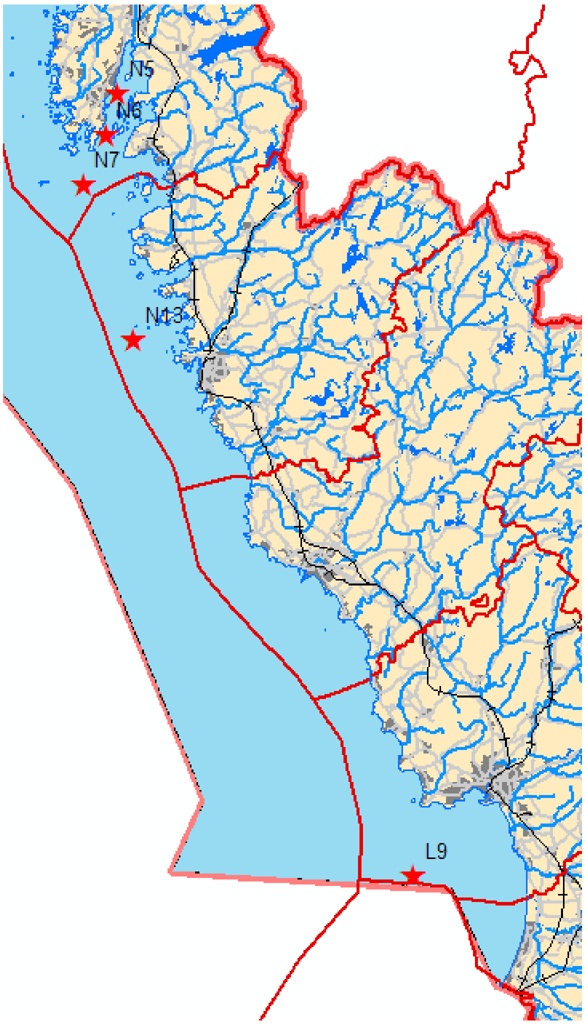

Figure 8: Hydrographic stations used for calibration and validation of the hydrodynamic model.

RESULTS

In this section some results and comparisons to observations will be presented. Some comparisons will be for the calibration period and some for the validation period. The purpose is to illustrate the degree of agreement between model results and observations.

In Figure 9 and Figure 10 the observed temperature and salinity at station L9 is compared to model results. Note the strong salinity stratification and the instances of vertical mixing creating almost homogeneous conditions. All in all the comparison is satisfactory, though of course there are disagreements, particularly in the timing of certain events.

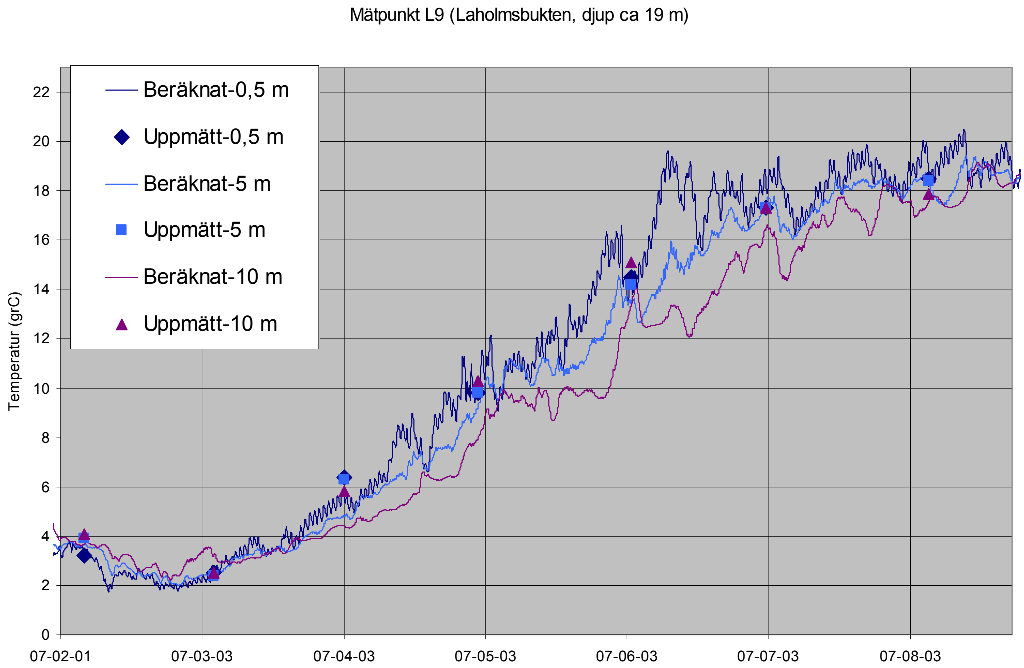

Figure 9: Observed (points) and modeled (lines) temperature (°C) at 0.5, 5 and 10 m depth at station L9 during the spring of 2007. Bottom depth approximately 19 m.

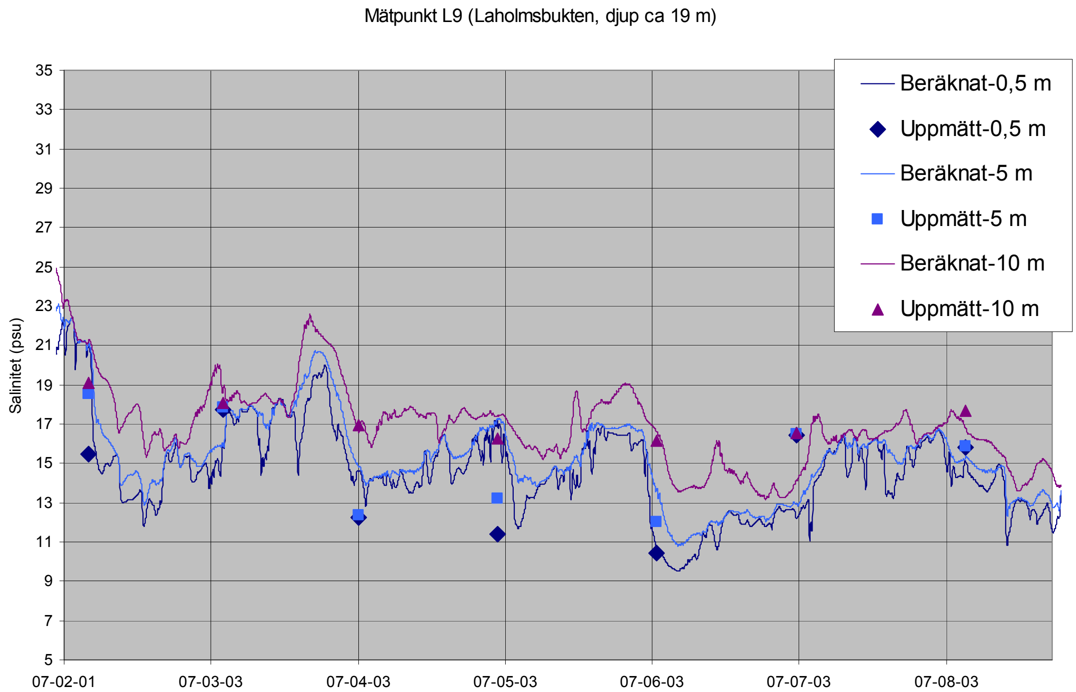

Figure 10: Observed (points) and modeled (lines) salinity (psu) at 0.5, 5 and 10 m depth at station L9 during the spring of 2007. Bottom depth approximately 19 m.

Figure 11 shows an example of the calibrated agreement between observed and computed river discharge for the river Fylleån. At least for the calibration period the agreement is fairly good, though the observed and modeled peak flows can differ by 50% or more.

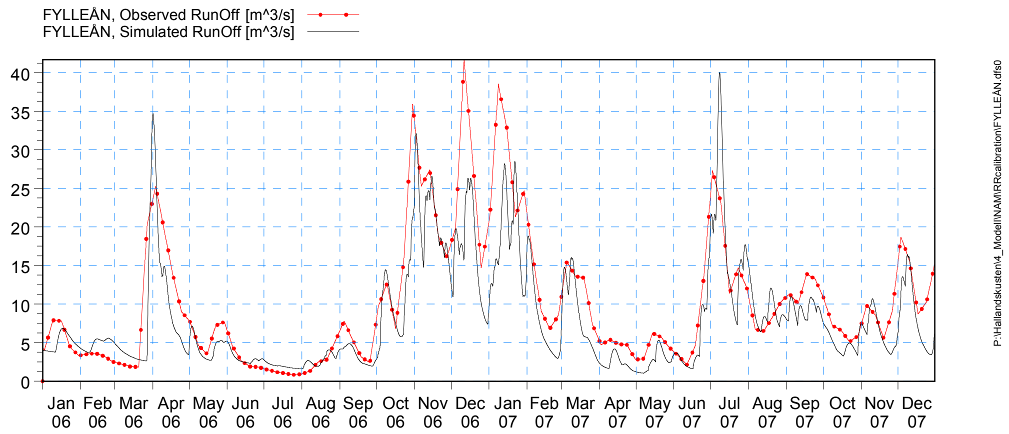

Figure 11: Computed (black) and observed (red) flow in the river Fylleån for the calibration period 2006-2007 (m^3/s).

If we look at the validation period (summer of 2009) we see that the agreement between modeled and observed river discharge is not always that good. In Figure 12 the observed and modeled discharges through the river Nissan have been plotted for the summer of 2009. The model clearly overestimates the discharge, often by 100% or more, even though the overall temporal evolution is fairly well described. Errors such as these in the river discharges, and associated sources of bacteria, should be kept in mind when evaluating the quality of the forecasts.

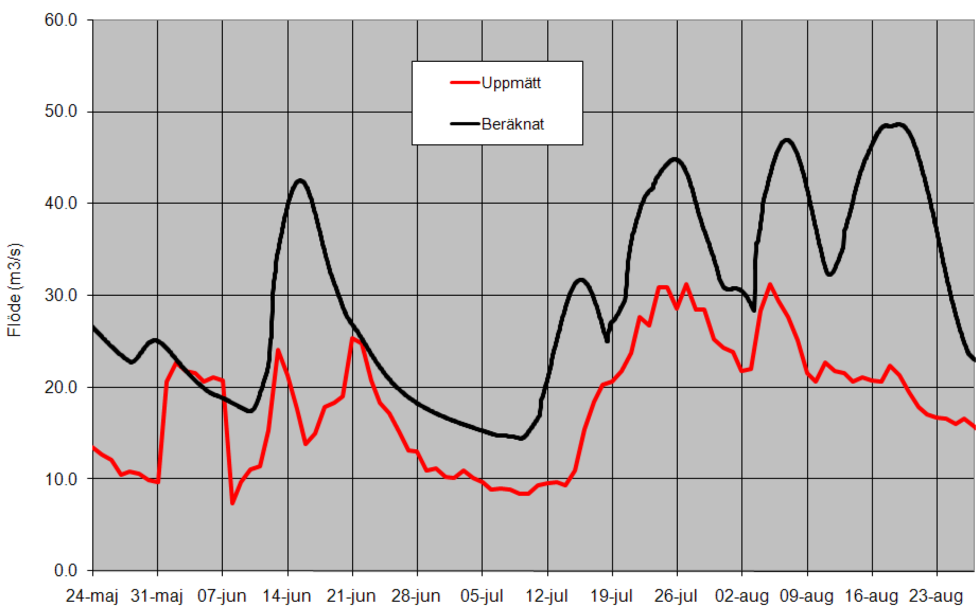

Figure 12: Modeled (black) and observed (red) discharge (m^3/s) in the river Nissan during the summer of 2009.

Next some comparisons with observed sea temperature and bacteria concentrations at different beaches will be presented. It should be noted that whereas the temperature primarily depends on the heat exchange with the atmosphere and the overall circulation – and thus does not vary excessively over short space and time scales – the bacteria concentrations are very sensitive to the sources and local hydrodynamic features, creating strong variations on short space and time scales. This means that much more data is required to accurately describe the space and time distribution of the bacteria concentrations, data which is not available.

Figure 13 shows a comparison for the beach at Bua. Clearly the sea surface temperature and its medium-term temporal variations are well described by the model. The modeled daily variability is not resolved by the measurements. The bacteria concentrations also show a reasonable agreement. However, the modeled variability is rapid and chaotic and it is difficult to say whether the instances of good agreement are a result of a good model or luck. Nevertheless, the ranges of the modeled bacteria concentrations match the observed range very well.

For the validation period in 2009 a more comprehensive analysis was carried out. For comparison, the modeled and observed sea surface temperature at the beach Bua is presented again (Figure 14). The agreement is still quite good, though in general the model slightly underestimates the observed temperatures.

The agreement between modeled and observed bacteria concentrations is summarized in Table 1. It can be seen that for intestinal *Enterococci* the agreement is good at most beaches but for *E. coli* it is poor at 50% of the beaches.

Finally, some model results pertaining to urban sources of bacteria will be presented. Overflows are by their very nature episodic, as is clearly shown by the model (Figure 15). This explains the short-term variability and chaotic impression of the modeled bacteria concentrations. Note that even though the flow rates are one or two orders of magnitude lower than those of the natural watercourses, the bacteria concentrations in the overflows are many orders of magnitudes higher than those in rivers and streams.

The corresponding storm water discharges are also episodic and to some degree correlated with the overflows (Figure 16), which is not surprising as they are both functions of rainfall. The storm water discharges are more common and release greater volumes, in the order of some of the smaller rivers.

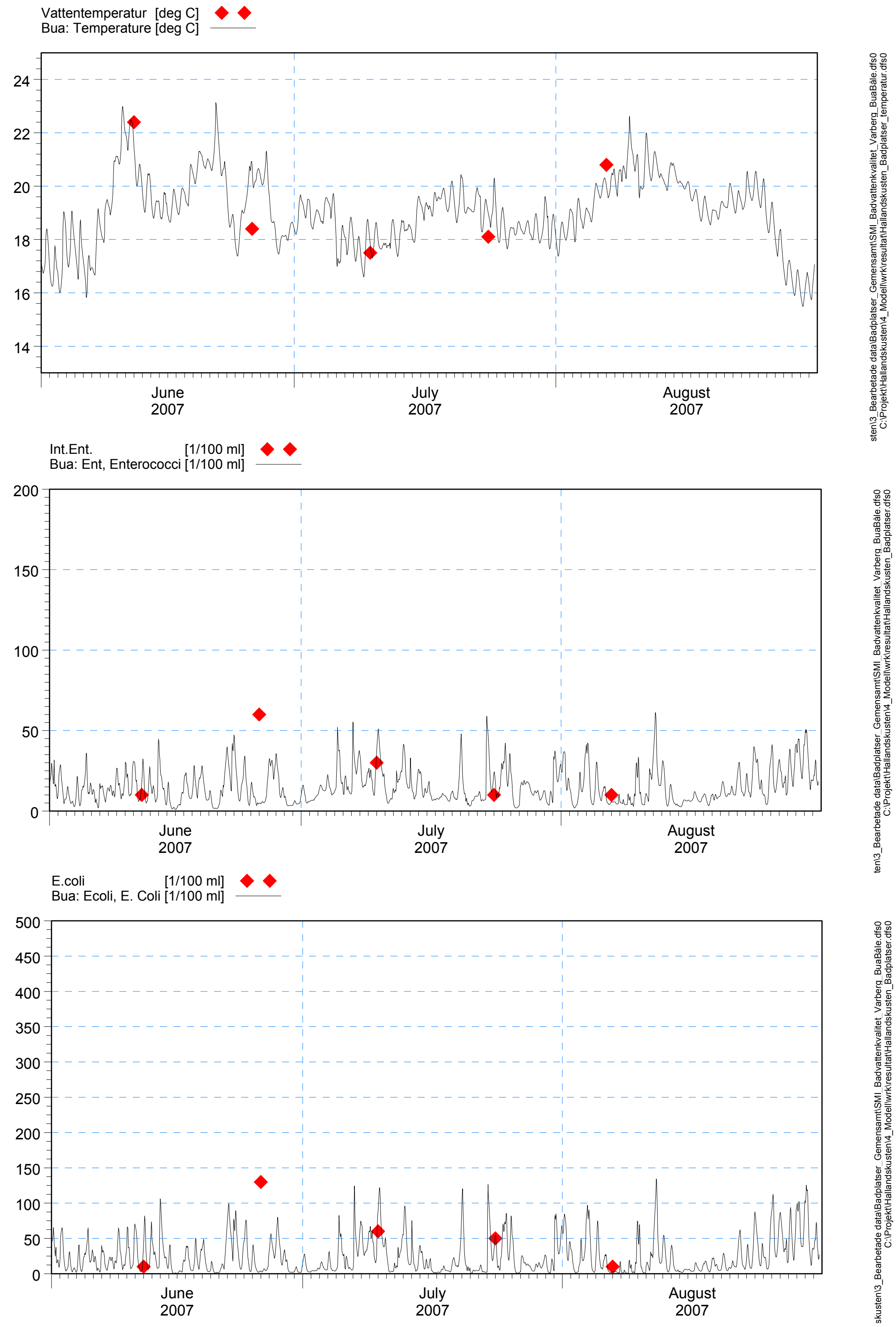

Figure 13: Observed (red points) and modeled (black lines) values for sea surface temperature (top; °C), intestinal Enterococci concentration (middle; cfu/100 ml) and E. coli concentration (bottom; cfu/100 ml) in the summer of 2007 at Bua.

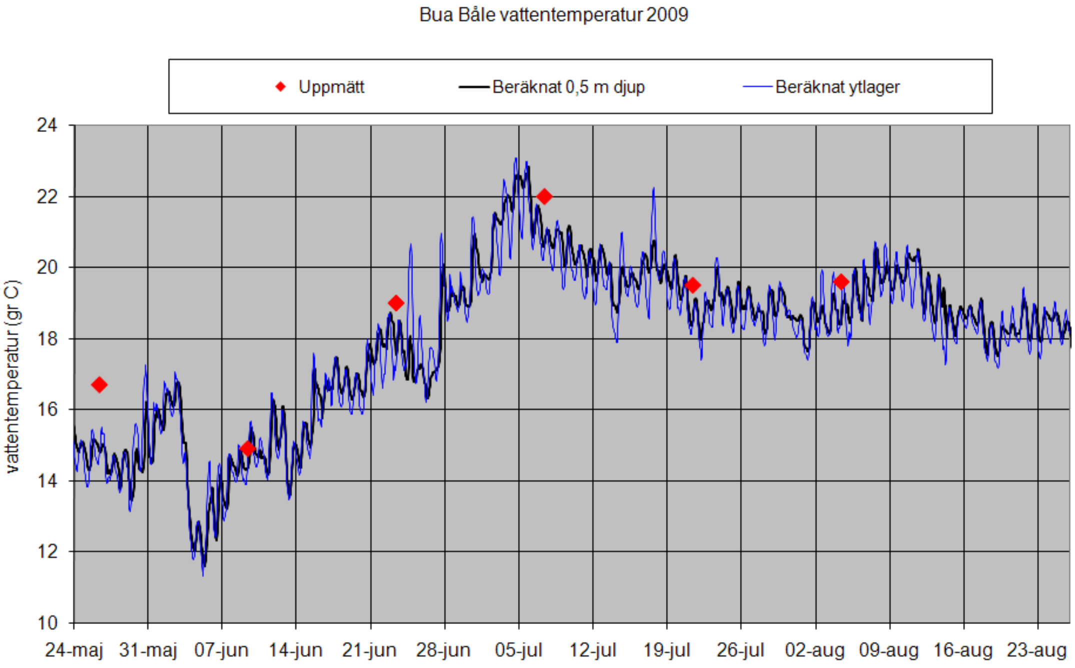

Figure 14: Observed (red points) and modeled (blue lines) sea surface temperature (°C) at Bua beach during the summer of 2009. The dark blue line is the modeled sea temperature at 0.5 m depth and the light blue line is in the topmost model layer (the layer thickness varies with the bottom depth but at this location it is shallower than 0.5 m).

Table 1: Estimated agreement between model results and observations of bacteria concentrations during the summer of 2009.

	Good agreement		Poor agreement	
Beach	Intestinal *Enterococci*	*E.coli*	Intestinal *Enterococci*	*E.coli*
Stråvalla	X	X		
Bua			X	X
Espevik	X	X		
Kärradal S	X	X		
Getterön 5			X	X
Getterön 1	X			X
L Apelviken	X	X		
Apelviken	X	X		
Träslövsläge	X	X		
Björkäng	X	X		
Steninge	X	X		
Haverdal	X	X		
Vilshärad	X			X
Ringenäs	X			X
Tylösand	X			X
Svärjarehålan			X	X
Gröningen	X	X		
L Köpenhamn	X	X		
Laxvägen	X			X
Birger Pers väg	X			X
Ejdervägen	X			X
Simvägen			X	X

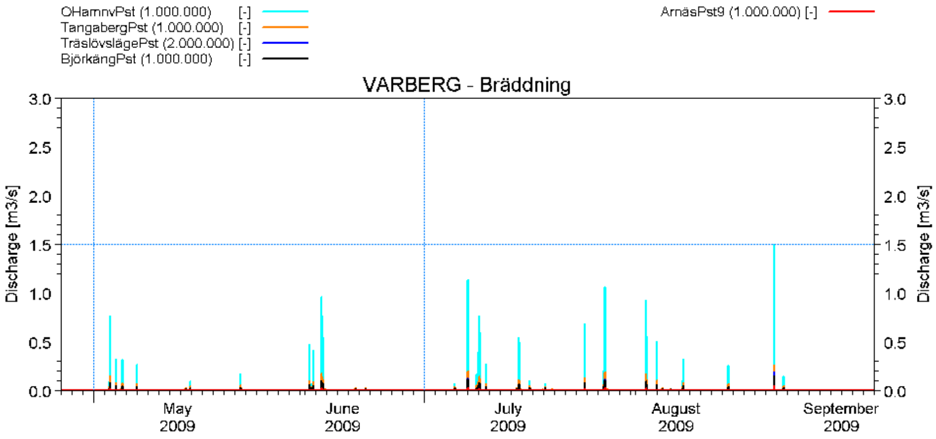

Figure 15: Modeled overflows in the municipality of Varberg during the summer of 2009 (m^3/s).

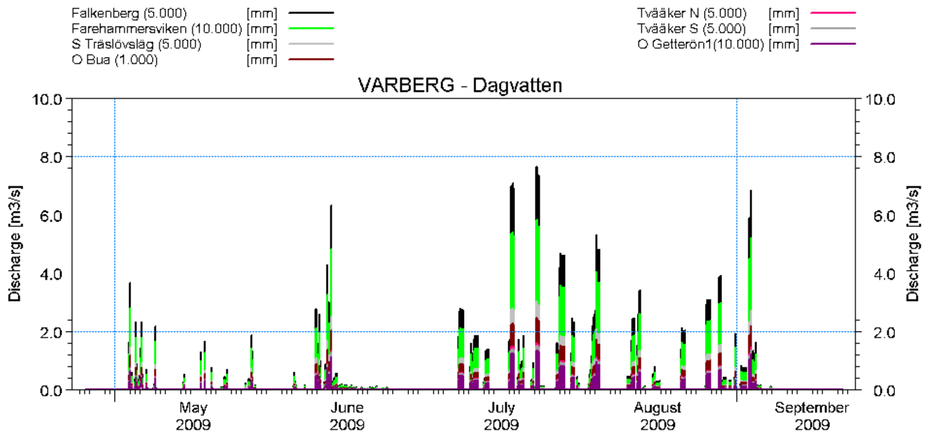

Figure 16: Modeled major storm water discharges in the municipality of Varberg during the summer of 2009 (m^3/s).

CONCLUSIONS

The bathing water forecasting system for the Swedish coast of Halland is now fully operational. All parts of the system are working as well as may be expected and no serious incidents have been reported over the summer of 2010.

Regarding the forecasting accuracy of the system this is of course very dependent on the accuracy of the forcing data. The validation that has been carried out indicates that the hydrodynamic model describes the dynamics of the stratification reasonably well. This also indicates that the meteorological forcing is reasonably accurate. However, it is important to realize that the system produces forecasts which will always vary in accuracy. For example, the air temperature in a particular point is very dependent on whether the meteorological model considers this point as part of a grid cell located over land or over sea (Figure 17). Since the resolution of the meteorological model is several tens of kilometers, this may produce unrealistic temperature forecast during periods of onshore winds at beaches which are closest to a land point in the model, or vice versa.

The issue of model resolution is of course always present. There will always be details in the current fields or meteorological fields that will not be resolved, as an increased resolution requires longer simulation times. For a forecasting system the simulations times must be kept down in order to produce forecasts when they are needed and not after. Hence, there is always a trade-off between resolution and performance.

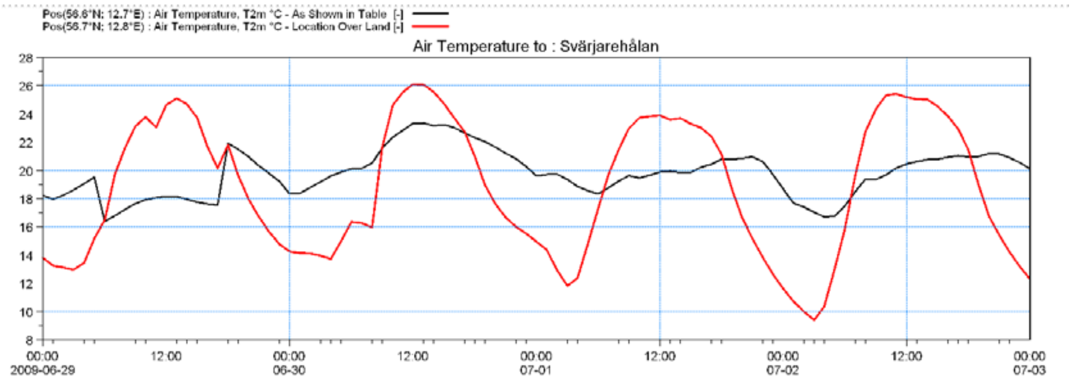

Figure 17: Forecasted air temperature in nearby grid points over land (red) and over sea (black).

Nevertheless, the results indicate that it is not the models that constitute the major problem in terms of accuracy of the forecasts, but rather the available observations and input data. Firstly, it is difficult to determine the accuracy of the predicted bacteria concentrations based on the limited data. The bacterial concentrations vary strongly both in time and space over scales that are nowhere near to being resolved by the sampling frequency and number of sampling points. Secondly, the input to the models that compute the load is limited. There are only a few precipitation stations available for calibrating the models and hardly any data on the source concentrations. Hence the bacterial load is probably only correct to within an order of magnitude. Thirdly, the forecasting system cannot take into consideration sources of bacteria that are unknown. It is an ongoing work to identify missing sources, a work that can be aided by using the model together with observed high bacteria concentrations.

Despite these problematic issues it is still a positive sign that for many of the beaches the model forecasts agree well with measurements (see Table 1). This indicates that the forecast system does serve its purpose of providing useful information to the general public and decision makers. It also means that continued work with identifying sources of bacteria and gathering more data will result in improvements for those locations where the agreement between observations and forecasts is poor.

Hence, to improve the accuracy of the forecasts the following suggestions are made:

- Carry out sampling of bacteria source concentrations and indentify missing sources. This field work should be focused on areas where problems exist or areas where the agreement is poor.
- Increase the number of precipitation measurements to enhance the spatial resolution of the precipitation pattern.
- Continue to improve the model system as more data becomes available.

It should be mentioned that during the summer of 2009 some human errors in the model setups resulted in an excessive amount of red flags, creating a great deal of worry among the general public and generating bad press in local media. The errors were easy to rectify and did not constitute any fundamental problems, but the lesson to be learned is that a system that is open to the public should never be allowed to go live until thoroughly tested under live conditions.

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