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Implementation of the water framework directive – can we use models as a tool in integrated river basin management?

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ABSTRACT
The implementation of the Water Framework Directive requires adjustment of the administrative structure for the water management in each of the Member States. Modifications of the procedures for river basin management are also foreseen. Today, river basin management in Denmark is for the most part carried out at regional levels (in 14 counties) and the environmental problems for freshwater systems in Denmark are mainly associated with diffuse pollution sources (primarily originating from agriculture) and pollution with pesticides and other xeno-biotics. Viewed in the context of the Directive river basin models may play an important role for a successful water administration – being tools in the technical solutions for how to achieve "good status" for groundwater and surface waters. In Denmark integrated river basin modelling is used in connection with restoration projects, also empirical models are widely used. The benefits from applying river basin models are manifold. Besides being able to evaluate "good status" for freshwater bodies based on hydrology, land-use, agricultural practices and ecology of individual river stretches (including lakes and wetlands), modelling can also identify solutions for flood/drought problems in combination with defining protection measures for the aquatic environment.

Keywords: Water management; water framework directive; model; water quality.

Introduction

In 1995 the European institutions agreed that a fundamental review and restructuring process was needed for Community water policies and in February 1997 the Proposal for a Water Framework Directive was adopted. Its purpose is to establish a framework in order to achieve the following four main objectives of a sustainable water policy:

- sufficient provision of drinking water
- sufficient provision of water for other economic requirements
- protection of the aquatic environment
- alleviation of the adverse impact of floods and droughts

The environmental objective of the Directive is to obtain "good status" for all ground-waters and surface waters within the European Union. To achieve this, river basin management basin should be established based on an assessment of the characteristics of the river; the monitoring of the status of its surface and ground-waters; the definition of quality objectives; and establishing programmes for measures to realise the defined objective. However, the administrative procedure to implement this river basin management is left to the discretion of Member States.

Mathematical models serve as tools for water management of river basins and modelling could be an important element of the practical implementation of the Directive.

In Denmark today, models are widely used by the water authorities ranging from very simple empirical (static) models for lakes (eutrophication, yearly mean values), monthly-based diffuse nutrient discharge models and up to fully dynamic models for rivers, lakes, groundwater and marine waters. The use of models, so far, has mainly dealt with specific environmental problems for selected river stretches, sub-catchment etc. Consequently, truly integrated models for the hydrological cycle of a given river basin simulating both surface water and groundwater compartments, impacts on river water quality from land-uses, point sources etc., as well as the influence on the final marine recipient, are not applied.

This paper addresses technical and administrative aspects of current Danish river basin management practices, the linkage to the implementation of the Water Framework Directive and the use of models as a tool for integrated water planning. For practical reasons the paper comprises freshwater systems only.

Water management in Denmark

Administrative structure

The management of the aquatic environment in Denmark is organised at three levels:

- National authorities, national aims and measures

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- Regional authorities (14 counties),
  - Protection of local water bodies, deciding quality standards for regional specific water bodies
- Local authorities (277 municipalities)
  - Protection of local water bodies, operation of public sewage treatment plants

National initiatives

A major national initiative during the last decades has been the implementation of the National Action Plan for Protection of the Aquatic Environment (1987). At the national level this plan aims at 50% reduction of the nitrogen and 80% reduction of the phosphorus emission to the aquatic environment. Hence the plan sets minimum standards for the acceptable outlets of nitrogen and phosphorus from major sewage treatment plans. Furthermore, the plan includes a wide range of measures to reduce the diffuse pollution of nitrogen from the farmed land covering around 2/3 of the national territory.

Another key issue for the national authorities has been the regulation of pollution by pesticides and other xeno-biotics. At the national level the general concept has been prevention of pollution by abandoning a wide range of the most harmful of these substances.

Regional initiatives

The main task for the regional authorities (counties) is to make regional water management plans. This includes setting-up standards for the physical development of the river as well as the water quality of specific water bodies. These standards should be fulfilled for each specific water body within the region, (streams, lakes, marine waters). The required pollution reductions from major sewage treatment plants are included in these plans. The counties, therefore, hold the option to decide more rigorous demands for maximum allowable outlets from such sewage treatment plants than those prescribed by the national minimum demands. Furthermore, the planning of drinking water supply and the implementation of measures to protect the groundwater used for drinking water is in the hands of the county.

Until now the counties have used, only to a minor degree, the possibility to implement measures for reductions of diffuse pollution from the farmed land within the county. The agricultural derived pollution is mainly regulated by nationally decided measures. These measures will not necessarily secure the quality standards of local waters.

The managing role of each county is restricted to the county territory. However, for some major catchment areas overlapping more than one county there is some co-ordination of the general environmental management. This is valid for some of the catchments discharging to the major Danish Fjords (e.g. Limforden, Mariager Fjord, Flensborg Fjord, and Lillebælt) and for the catchment area of the longest Danish stream, (River Gudenå). Thus, the counties in Denmark have already co-operated for many years on protection of large water bodies crossing regional and national borders. This co-operation is expected to be more formalised and to include all water bodies with the implementation of the Water Framework Directive.

The local authorities (277 municipalities) have some minor environmental management tasks, of which the major one is the operation of the public sewage treatment plants handling most of the sewage produced. It is up to the local authority to operate these plants in compliance with the demands prescribed by the counties. For minor point sources such as single sewage outlets from scattered dwellings, which are not connected to sewage treatment plants, the local authorities holds the responsibility for regulation of these outlets based on the quality standards for the local waters set by the counties.

Information on water quality of watercourses and impact factors

Assessment of the environmental status of water bodies, the impact factors and the making of standards for the quality and proper management of the waters has been a task for the counties since the beginning of the 1970's.

Since 1989 supplementary assessment of the actual quality of aquatic environments and the general development has been provided by a comprehensive standardised nation-wide monitoring programme covering all compartments of the hydrological cycle. The programme includes assessment of the impact factors (sewage, farming, etc.). The monitoring programme focused on nutrient pollution until 1997, but a major revision of the programme introduced the monitoring of pesticides and other xeno-biotics. The Danish counties perform most of the actual monitoring and evaluate the results in regional reports. Relevant research institutions make final nationally summary reports based on the data collected by the counties. Besides the nationwide standardised monitoring programme the counties also carry out regional monitoring adjusted to the local needs for proper management of the county waters.

Main environmental problems today

In Denmark focus were on the minimising pollution from point sources (industrial outlets and domestic sewage) during the 1970–1980's.

Today the main environmental problems comprise:

- Diffuse pollution (nutrients) to surface waters
- Leakage of nitrate, pesticides and other harmful substances to groundwater
- Ecological status of surface waters, especially minor streams
- Pollution of surface waters with pesticides and other harmful substances

Although the phosphorus outlets to freshwaters have been reduced significantly during the last decade, due to improved sewage treatment, it is evident that the national aim of reducing nitrogen outlets by 50% is far from being fulfilled, see Figure 1. Around 80% of nitrogen outlets to Danish freshwaters are caused

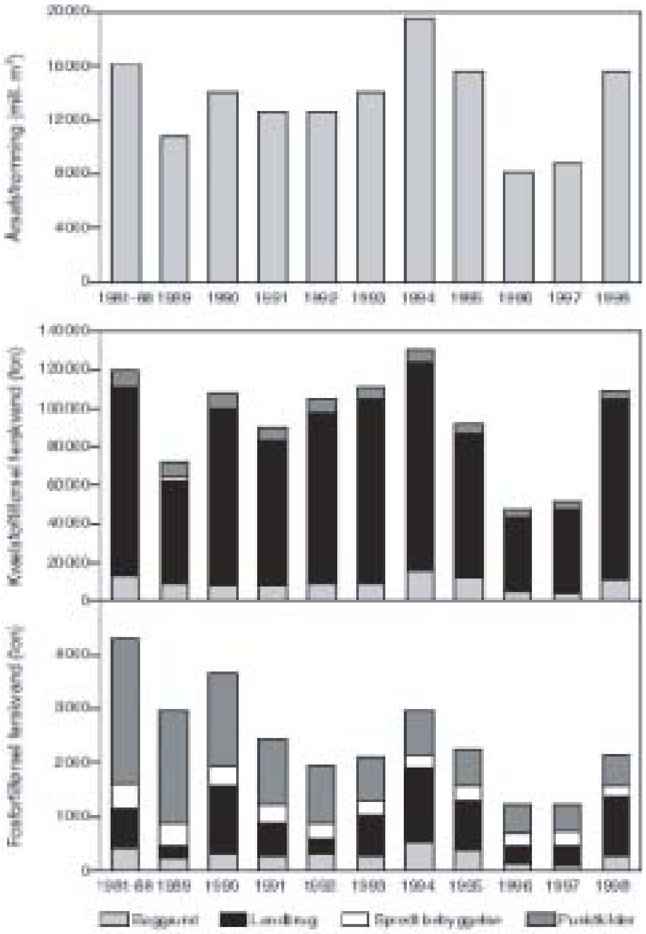

Figure 1 Discharge of water, nitrogen and phosphorus to the Danish surface freshwaters (from [2]). Black: agriculture, white and grey (upper): sewage, grey (bottom): background.

by diffuse pollution from farmed land. Also the diffuse outlet of phosphorus is significant.

This causes eutrophication of the Danish lakes and inner coastal marine areas. Consequently, the quality goals decided upon are only met for about 1/3 of the Danish lakes [1].

Although drinking water compartments still has an acceptable quality it is evident from the monitoring programme that leakage of nitrate, pesticides etc. is a serious treat to the future drinking water quality. Thus, more than 10% of the groundwater (0–20 m) has a content of pesticides, which does not meet the acceptable quality standards [1].

Finally, the ecological quality of many streams is not acceptable. Therefore only around 40% of the streams meet the Directive for quality standards [1].

Implementation of the Water Framework Directive (WFD) in Denmark

The practical implementation of the Directive in Denmark calls for a decision about the procedures needed for the prescribed catchment related co-operation between the regional environmental managers. As stated in the foregoing, in Denmark today, water quality planning and management primarily is in the hands of the counties.

However, at the time of writing this paper it is unclear how many catchment areas will be selected in relation to the WFD.

A number between 5 and 10 new WFD-catchments may be a realistic estimate. Though, it must be remembered that the aquatic environment within the borders of the future major catchments prescribed the Directive still will be a mosaic of very many specific minor waters (lakes, ponds, streams, minor fjords, etc.). These waters still need to be managed properly and in Denmark the counties have the experience in doing so. Hence, it must be avoided to select too few WFD-catchments because this could lead to a decreased focus on and solution of local specific environmental problems.

Furthermore, the authors want to stress that in order to keep public awareness and political decisions closely linked, it is important to continue with river basin management at the regional level. Moreover, it is important to establish consensus for proper management tools and to focus on regulations for control of diffuse pollution. Control of diffuse pollution should not only focus on major catchments, also access to proper tools for a spatial diverse management of diffuse pollution is essential.

There is an urgent need for a discussion in the Member States of how "good status" for groundwater and surface waters should be interpreted. In Denmark we follow a water management practice, which may not be ideal, but it has been operational. The management practice has focused not only on defining acceptable quality standards of the different waters, but also – and wisely maybe even more – on pinpointing the major anthropogenic impacts and subsequently managing these impacts through plans adjusted to solve the environmental problems in specific waters.

In many ways the Directive is in line with the administration we have today. For instance, when we define the water quality objective for a river stretch we take into account pollution from point sources and diffuse sources and their impact on the water status. Based on these considerations a realistic objective is defined – balanced with the natural conditions of the watercourses. We also identify surface waters and groundwater intended and/or used for drinking water abstraction and implement protection measures where needed. Consequently, the integrated and holistic approach put forth in the Directive is not so different from the Danish water administration today and the implementation in Denmark may be without severe difficulties. Economical considerations for the different water uses (water as an economic good) are perhaps a new aspect for the Danish water authorities to include.

River basin modelling in Denmark

Empirical models

During the past ten years several simple, purely empirical-based models for nutrient run-off and retention in freshwater systems have been developed. Data for monitoring stations covering all parts of Denmark have been compiled and via multi-regression analysis transformed into simple equations for retention in streams and lakes. Typical input data to such empirical models are yearly N and P loads, mean water flow, depth of the system and yearly residence time of the water body. The usefulness of such models in the water administration is high as one can quickly make rough estimates of e.g. benefits gained from nature restoration projects using empirical models.

Dynamic models

Dynamic models are also widely used in the Danish water administration, in particular in connection with water level/flood protection regulations, which require physical-based models.

The well-known MIKE systems developed by DHI is installed at most Danish water authorities. MIKE 11 is a comprehensive, one-dimensional modelling system for simulations of flows, sediment transport and water quality in estuaries, rivers, irrigation systems and other water bodies [3]. MIKE SHE is a three-dimensional model for water flow and water quality in rural catchments. MIKE SHE simulates all major processes occurring in the land-phase of the hydrological cycle [4]. The two models can run simultaneously meaning that the hydrology and water quality is calculated with a true physical-based river basin model for groundwater compartments as well as surface waters. The models have been designed in a modular structure with basic computational modules for hydrology, hydrodynamics, advection-dispersion, water quality and sediment transport. As an integrated part of MIKE 11, the MIKE 11 RESERVOIR model can be applied for deeper water bodies (e.g. lakes or reservoirs). Both models are constructed around three main application areas, all of which may be important for the river basin management:

- Hydrology and Hydraulics
- Water quality and ecology
- Sediment processes

Data requirements and limitation

The data requirement for integrated river basin modelling, comprising surface run-off and groundwater dynamics as well as surface flow can be separated into two main groups: (1) basic data for the river system and its associated water bodies and (2) the basin-specific environmental data, which are subject to human intervention. Basic data comprises:

- Topography and land cover
- Geology and soil type
- Rainfall and evaporation
- River system (cross-sections, structures etc.)
- Water levels
- Discharge and flow velocities

The above-listed basic data deals with water quantity related issues. Data to drive environmental modelling on top of the water models consist of the traditional water quality parameters and information on the catchment area. River basin specific data on parameters being subject to human intervention are:

- Land-use, e.g. cropping pattern
- Agricultural nutrient/pesticide application
- Other aspects of agricultural practise (e.g. tillage and crop rotations)
- Point sources (industrial loads, domestic sewage, sewer overflow etc.)
- Water quality in rivers, streams and lakes
- Ecological parameters
- Wetlands (flooding period, transformation processes etc.)

Generally, the most limiting factor for detailed modelling is to obtain reliable data for the diffuse loading. Diffuse sources by nature are difficult to measure and control, but data for land cover, agricultural practices exist and can be transformed into diffuse loads using run-off models. These data are, however, difficult to access and therefore only to a minor extend integrated in the overall river basin planning.

Applications

In the following three examples of application of river basin models for different areas in Denmark are presented.

Example 1: Gjern River Basin – Retention of nutrients

In Denmark, as in many other European countries, the diffuse losses of nitrogen and phosphorus from the rural landscape are the major causes of surface water eutrophication and groundwater pollution. As part of the Danish Environmental Research Programme (1993–1996) a study for nutrient retention in a typical Danish river basin was conducted [5,6]. The aim with the study was to develop and set-up a modelling system for a river basin with specific descriptions for retention of nutrients in streams, lakes and riparian wetlands. The modelling system, called TRANS, consisted of a dynamic model for water flow and nutrient transport in surface waters (MIKE 11) and an empirical-based description of nutrient retention in each of the three main water bodies. The long-term objective is to develop an integrated decision support tool for transport and accumulation of nutrients in freshwater systems based on simple empirical models with a low data requirement. The model was calibrated for the hydrological year June 1994 to May 1995. Various scenarios were hereafter calculated with the model, including:

- Restoration of the river to the situation found on maps from the 1870’s (natural cross-sectional dimensions and dredging of P-enriched lake sediment)
- Extensivation of agricultural areas
- Abatement of point sources (wastewater treatment plants and fish farming)

In Table 1, N loading to the entire system, the calculated retention due to self-purification processes and the export to downstream recipients are shown for selected scenarios. As can be seen, it is possible to reduce the total load to the surface waters by about 45% and the export to the downstream recipient by about 40%. The difference is due to a reduction in the self-purification efficiency with lower nutrient levels.

Table 1 Comparison of N Loading (point source + diffuse), calculated retention and export to downstream recipient

Scenario	Loading (tonnes)	Retention (tonnes)	Export (tonnes)
Reference, 1994/95	215.8	38.8	177.0
Restoration, year 1876	215.8	51.4	164.4
Reduction, point sources	187.3	21.7	165.6
Extensivation (20%) agriculture	150.0	25.4	124.6
Restoration, ultimate	121.6	13.2	108.4

Example 2: Skjern River Basin – A sustainable river management solution

The restoration of the Skjern River is the largest project of its kind in Northern Europe (catchment area about 2500 km^2, restoration stretch about 20 km). The restoration project is unique in its size, in public awareness around it and in the technical difficulties it has dealt with. The key objectives were to return the river to its original meandering course, to create permanent wetlands, to increase the biodiversity in the river valley, to improve the conditions for trout and salmon and to increase the nutrient turnover of the system. A key requirement for the restoration project was that no decrease in the flood protection standard would be acceptable outside the project area.

A detailed mathematical modelling study was carried out as part of the design study for the restoration scheme [7]. The findings of the study are the following:

- Extreme flood levels will decrease, medium flood levels will be more or less unchanged and low flow levels will be higher, see Figure 2
- The conditions for salmon and trout will improve significantly with re-meandering of the river
- The restoration project will contribute significantly to the reduction of nutrient inflow to the downstream marine area
- The future conditions is manageable in the sense that small interventions, e.g. reopening of ditches or alteration of levee heights can change the conditions at flood plains significantly

The project has now completed its implementation and a comprehensive monitoring programme has been established to monitor the development of physical and biological conditions closely. The monitoring programme will form the basis for nature management of the area and will constitute a valuable database for future nature rehabilitation and restoration projects.

Example 3: Vojens/Haderslev River Basin – Impacts of wetland/lake restoration

The enhanced nutrient retention due to re-establishment of drained wetlands and lakes provides a secondary benefit in addition to the direct recreational value. In order to quantify the increased retention of nutrients from different restoration projects in the southern part of Denmark (Vojens/Haderslev River Basin), a one-dimensional model (MIKE 11) was applied on a watershed level. The model describes the hydrodynamic and the biological processes in different but interconnected freshwater ecosystems (streams, wetlands and lakes).

The implementation of large and costly wetland restoration projects has called for methods to quantify the environmental effects for the downstream recipient. The traditional technique, which consists of comparison of measurements taken before and after the nature re-establishment, has shown to be inadequate for determination of the actual effects as the meteorological variability within and between the seasons strongly controls the nutrient retention. Using a calibrated mathematical model, the same set of meteorological data are applied for the situation before and after the restoration and the differences between the two simulations are solely caused by the nature re-establishment.

The river system also included two shallow and non-stratified lakes, which were modelled with a eutrophication model as

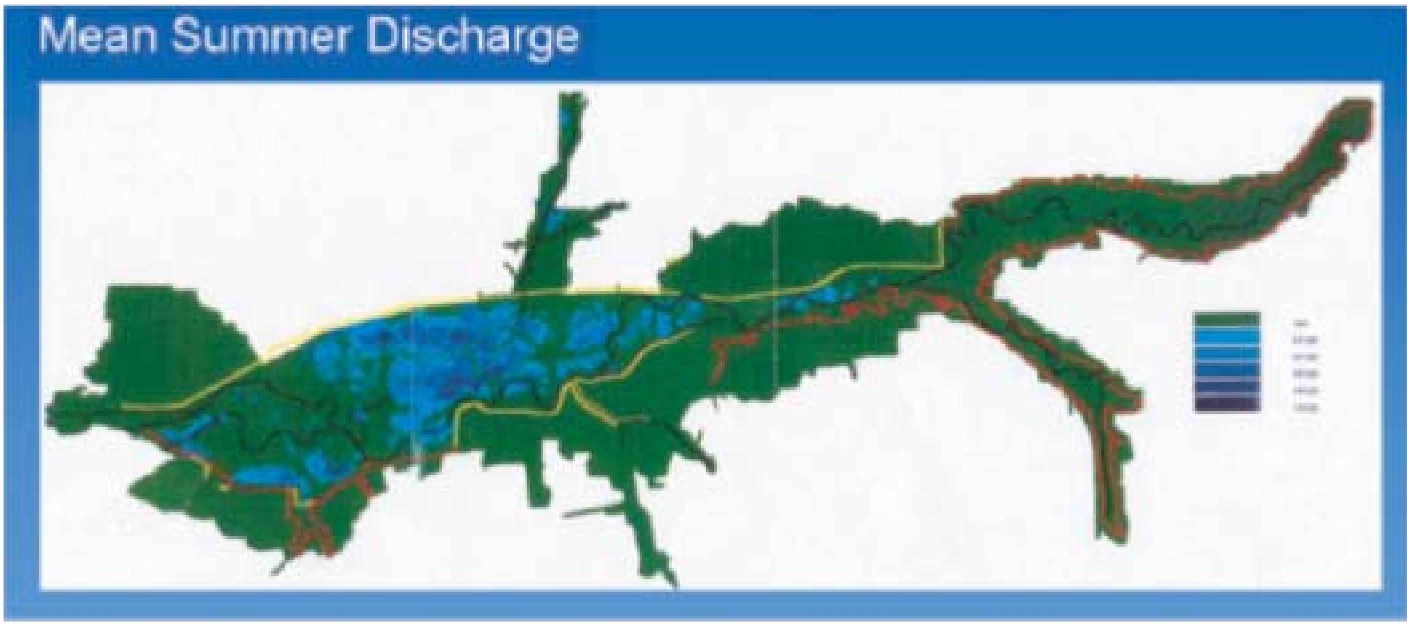

Figure 2 Flood map representing a mean annual flood.

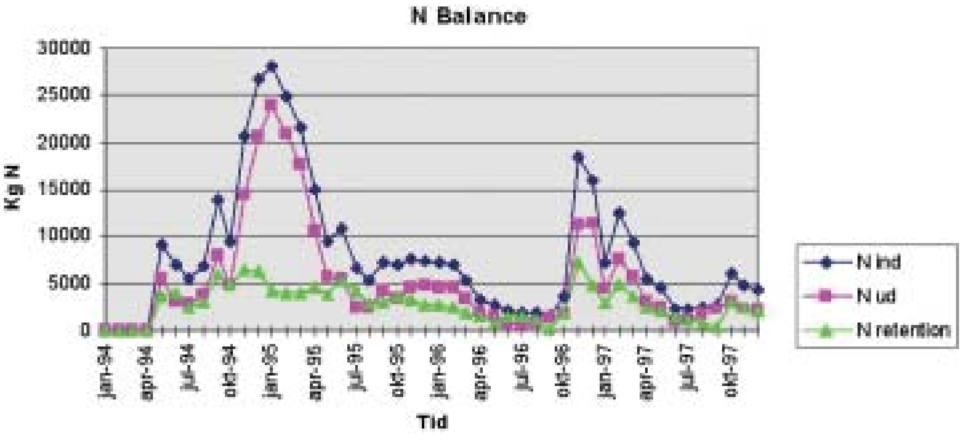

Figure 3 Simulated N balance for an artificially created wetland.

well as riparian meadows, which were modelled with a wetland model. The integrated modelling system was applied to assess the impact on the retention of nutrients from already implemented and several proposed restoration projects within the watershed. In Figure 3 the calculated N balance for an artificial wetland within the river basin is shown. The yearly N retention amounts to about 50 tonnes. Among the proposed restoration projects, excavation of sediment in the largest lake – Lake Haderslev – and its impact on the lake water quality was studied with the model. The lake sediment is rich on phosphorus due to discharge of domestic sewage to the lake over the past 30–40 years. However, ten years ago the pollution load was strongly reduced as wastewater treatment plants with chemical treatment were constructed to treat all major point sources in the area. Nevertheless, the release of phosphorus from the lake sediment (internal loading) even ten years later is much higher than the external phosphorus loading to the lake and algae blooms together with very high summer Total-P concentrations ($>650\,\mu$g/l) have been observed during the past five years.

Simulations with the modelling system revealed that the lake will act as a source for phosphorus for the next 10–15 years before equilibrium between phosphorus in the water column and the content of phosphorus in the sediment is reached. The model predicts that hereafter the lake will return to its natural function as a sink for phosphorus (10–20% of the total load will be retained) and that the lake water quality gradually will be improved over this 10–15 years recovery period.

Case study – Funen

As already mentioned 14 Danish counties are responsible for the water quality planning, monitoring etc. in the respective regions. Among these is the county of Funen, which is situated in the middle of Denmark. The administrative region covers 3486 km^2 of which 2/3 are farmed lands. Approximately 0.5 mio people live in the region. Domestic sewage is treated at 114 sewage treatment plants. Sewage produced from about 50.000 persons is, however, not connected to the central sewage treatment plants.

The region consists of about 90 islands with a total shoreline of approximately 1100 km^2. The county is responsible for managing the water quality in the inner coastal waters including 40–50 specific fjords and bays. Approximately 3400 km open streams and canals drain the total catchment and there are 24 lakes ($<0.1\,km^2$) within the county. For these specific watercourses too the county is the key manager. The water supply for drinking water is derived from groundwater. 272 waterworks abstract water from 690 wells. The abstraction by these waterworks amounts to 80% of the total water abstraction in the county. Moreover 8.000 single wells in the open land supply water to households not connected to the public drinking water supply. To a certain degree the abstraction of groundwater affects the water flow in some of the streams draining the county.

For the county of Funen too the environmental problems are mainly related to the diffuse pollution. In the river basin management different models are used. However, for some areas/problems proper models relevant for planning and analysis are lacking. Below a brief overview of applied models in the daily management is presented. Comments regarding models (and data), which would be beneficial to include in the regional and local management of the aquatic environment, are added.

Models used in the river basin management

Objective: Drinking water protection. In the decades to come, the supply of drinking water with a good water quality requires an enhanced protection of drinking water reservoirs against the increasing pollution from diffuse (agriculture) and/or point sources. Therefore specific attention will be directed towards the groundwater resources in 30 areas. For this models are suitable tools as the hydrological cycle and the leakage of pollutants are simulated simultaneously. It is anticipated that an area covering 3–5% of the county territory will be protected against diffuse pollution by rigorous restrictions for agricultural practice. **Model used**: MIKE SHE.

Objective: Lake management. For lakes, in which the water quality does not meet the Directive for quality standards, the external nutrient loading has to be reduced. **Models used**: Simple empirical eutrophication models with a linkage to the external nutrient load, with which forecast simulations of the environmental benefits of reducing external nutrient loading are made.

Objective: Determination of run-off and nutrient loading from areas where no measured data are available. For about 50% of the county territory water and nutrient discharges have to be estimated using models. For many lakes a significant part of external nutrient loading can only be calculated by estimates/models. **Models used**: Simple empirical county specific relations/ models. More detailed models including agricultural practice etc. would be beneficial.

Objective: Nutrient balance for the agriculture in the county including trend analysis. In order to follow the development of the diffuse sources analysis corrected for meteorological variability is required. **Models used**: Simple mass balance calculations. The use of standardised and well-proven models would be beneficial. An improved access to agricultural statistics is strongly needed. The same applies for analysis of nutrient run-off from sub-catchment with different land-use, population density, agricultural practices, soil types etc. A model that can address these factors, and via aggregated information (e.g. GIS maps) is able to calculate the resulting run-off of nutrient, pesticides and other xeno-biotics to the watercourses is strongly needed. The model should not necessarily be a detailed physical-based model, but should be able to make the calculations based on easy-accessible data.

However, for a more basin-wide analysis and to implement a holistic water management, a true river basin model with all its compartments and inter-related water and mass dynamics is needed.

Conclusion

In connection with the implementation of the Water Framework Directive in Denmark it is necessary to agree on new procedures for co-ordination of the water quality planning and management.

In order to preserve the constructive relationship between the local politicians, the local population and water managers, the authors, however, believe that regional water management is required. Furthermore, in order to control and implement sustainable regulations to combat the diffuse pollution, which is the main environmental problem for our freshwater systems, regional and basin-wide planning is essential. It is not only essential in relation to the forthcoming WFD-catchments but also in smaller scales, i.e. specific catchments to groundwater abstraction wells, catchments to specific lakes, fjords, etc.

Viewed in the context of the Directive river basin models may play an important role. Holistic modelling of river basin hydrology, hydrodynamics and water quality, taking into account the origin of non-point pollution and ecology of individual river stretches (including lakes and wetlands), is recommended. River basin models can provide information about e.g. the chemical status of the freshwaters, being tools for development of measures to realise the defined objectives as well as provide solutions for flood/drought problems and protection measures for the aquatic environment. All in line with the Water Framework Directive. So the answer to the question “Can we use models as a tool in integrated river basin management?” – is yes!

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