Selection of models for the development of the Information and Decision Support System (IDSS) for the EU-Interreg-IIIB-Project: nature oriented flood damage prevention

Report prepared at German Federal Institute of Hydrology

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Bericht

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Preface

This report describes the activities I carried out during my internship at the Bundesanstalt für Gewässerkunde (BfG) in Koblenz, Germany. This internship took place from August till December 2004 and was in accordance with the compulsory internship that forms a part of the study Civil Engineering at the University of Twente in the Netherlands.

Because of the great support I received during this internship, I would like to thank some persons here. First of all, I want to thank the staff members of the 'Auengruppe' at the department of ecological interactions at the BfG for giving me the possibility to carry out my internship in Koblenz: Elmar Fuchs, Volker Hüsing, Peter Horchler, Stephan Rosenzweig, Anke Hettrich, Helmut Giebel, Günter Dax, Beatrix 'Suzi' Konz and Alfred Hommes. In the second place, I would like to thank Jean-Luc de Kok for the support from the university. Thereupon, I want to thank the other members of the nofdp working group for giving me the opportunity to carry out my internship at such an exciting project and to see in praxis what I only knew from the theory: Prof. Manfred Ostrowski, Axel Winterscheid, Christoph Hübner, Piet van Iersel, Matthias Sottong, Ron Lambregts, René de Louw and Marcel van Betuw. Finally, I would like to thank all the interviewed persons, Michiel Blind from RIZA and Peter Gijsbers from WL Delft for providing me the information about respectively the available models and the Open Modelling Interface. Without the help of these persons, I would not have reached this result.

Summary

The consequence of the rising needs of the world population is that the level of competition for scarce natural resources increases. This results in an increasing complexity of river basin management problems and the need for Decision Support Systems (DSS). The objective of the nofdp project is to develop an Information and Decision Support System (IDSS) that can assist governments in making optimum decisions for riverine planning. The nofdp project sets out to use existing models as much as possible. However, it was not clear which models can be useful for the IDSS and how these models can be coupled within the IDSS. Hence, the aim of this study was to give recommendations about the application of available models in the IDSS.

From literature research, it became clear that the two most often used approaches for the design of the model base of a DSS are the top-down approach (purpose-driven) and the bottom-up-approach (model-driven). It could also be found that in most DSS development projects in the past, a combination of end-user, scientific, technical and organisational criteria was used for model selection. To find out the best way in which models can be coupled, projects that are in just an early stage as nofdp often use techniques like information flow tables (IFT).

Because no well-defined system diagram is available at the moment and due to the constraint of reuse of models, the choice was made to carry out the model selection by means of a bottom-up case study and model coupling by means of an IFT and a search for appropriate coupling techniques. Between model selection and model coupling in turn, an iterative process took place. Selection criteria were generated out of criteria that were used at other DSS development projects and the special features of nofdp.

The advise is given to implement a core of the IDSS model base consisting of two scale layers and a number of model components for each layer. For the catchment layer, a combination of SOBEK-RR or DUFLOW-RAM, SOBEK-CF and SOBEK-quality is suggested. For the local scale layer, a combination of SOBEK-CF, MODFLOW and some other detailed models is suggested. Balancing the output generated and the input required by these models has allowed to design a structure with some iterative data flows between the models to simulate interaction. To provide maximum flexibility and maximum possibilities for reuse, an application framework like the Open Modelling Interface (OpenMI) is recommended to implement this structure. The OpenMI provides a sufficient and well-defined set of interfaces, that allows for the reuse of existing models which are available for the creation of integrated models.

Contents

Tables

Figures

1. Introduction

This report is the tangible product of an internship study that was carried out at the Bundesanstalt für Gewässerkunde (BfG) or German Federal Institute of Hydrology in Koblenz. This internship took place in accordance with the nofdp project that has the aim to develop an Information and Decision Support System. More information about Decision Support Systems and the nofdp project can be found in this introduction, together with a description of the problem framework and the layout of the report.

1.1 Decision Support Systems

The inevitable consequence of the rising needs of the world's population is that the level of competition for scarce natural resources increases. In former times, when the pressure on the environment was at a lower level and there was a large natural buffer in the system, it was possible to consider problems largely in isolation. Then, the effects of any given decision were usually local. Nowadays, this is no longer the case. An apparently beneficial decision in one area of policy or operation can have major less desirable effects elsewhere, in both the natural and man-made environments. Frameworks for *integrated River Basin Management* (RBM), like the *Water Framework Directive*, are intended to address this issue by creating regulatory and other organisations whose aim it is to consider the competing uses for environmental resources and attempt to develop sustainable polices for their use.

Implementing integrated RBM presents many challenges because it involves making highly subjective value judgements about matters that are not directly comparable, for example, reducing river pollution versus the need to maintain employment. The complexity of environmental processes and the ways in which they interact only increase these challenges. Indeed, the problems are so complex and require so much understanding of the system, that appropriate integrated RBM is beyond the capacity of human beings. Hence, *Decision Support Systems* (DSS) need to be developed to assist in RBM.

A DSS usually consists of four components (see figure 1-1):

- A *user interface*, enabling easy interaction between the user and the system.
- A *data base*, containing the raw and processed data of the domain and the area at study.
- A *model base*, with relevant models, used to predict the likely outcomes of pursuing different policies for given scenarios.

- A *tool base*, with the methods, analytical techniques and software instruments required to work in an effective manner with the domain models and the data.

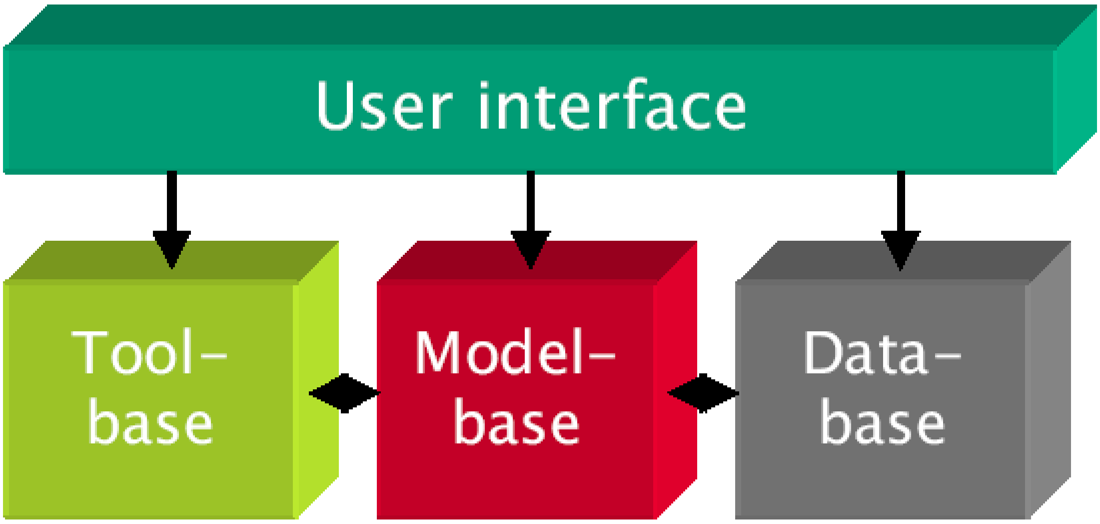

Figure 1-1: Basic functional components of a DSS (Hahn et al., 2000a)

DSS have become ever more sophisticated during the last years as it was attempted to model and to understand more and more of the likely consequences of following any particular policy, for example, the ecological effects of river regulation. It is not yet feasible to have a single *model* of all the processes taking place within a catchment. Hence, during the coming years, model linking will be used to simulate complex processes.

1.2 The nofdp project

Taking into account the above mentioned requirement of an integral river basin management, four German partners (Hessian Ministry of the Environment, Rural Development and Consumer Protection; Darmstadt University of Technology; the BfG and *water board* Mümling) and four Dutch partners (Province Noord-Brabant and water boards Aa en Maas, Brabantse Delta and De Dommel) started the nature-oriented flood damage prevention (nofdp) project in the spring of 2004. This is an INTERREG IIIB NWE Project, a programme that supports transnational co-operation in the field of spatial development. The overall objective of the nofdp project is to develop an information and *knowledge base* as well as decision support tools to assist member states of the Northwest European (NWE) region in making optimum decisions for riverine planning considering ecological improvement for river corridors with a high degree of public participation, spatial development and flood damage prevention (Winterscheid et al., 2004).

This target is supported by four real world investment projects located in The Netherlands and Germany having well developed scenarios for flood damage prevention planning. With an interactive process among the investment group (in charge of construction, i.e. the water boards) and the so-called development group (experts and specialists i.e. Darmstadt University of Technology, BfG and Province Noord-Brabant) the Information and Decision Support System (IDSS) will be developed.

Next to the functional components of figure 1-1, a knowledge base containing multi-sectoral assessing schemes, national conventions and EU-regulations related to various sectors (e.g. spatial planning and ecology) is introduced. In an iterative process, the IDSS is tested and refined by applying it to present planning scenarios of the investment projects. The application phase then will result in generating future scenarios of planning alternatives. Evaluating these scenarios by the multi-sectoral transnational assessment patterns will give recommendations about which planning scenario meets the demands of both flood damage prevention and ecological improvement of river corridors to the largest extent. Future application of the IDSS in the NWE-territory then will help in establishing a coherent network of de-central flood control measures as part of an integrated RBM considering ecological, spatial, economical, administrative as well as technical aspects on local, regional and transnational scale.

1.3 Problem definition, purpose and research questions

To accomplish the development of the model base, the nofdp project set out to evaluate, select and potentially adapt existing models that are used at the different project partners, particularly the water boards, as much as possible. However, it was not exactly clear which models are used and what the application domains of these models are. Next to this, it was unclear which models can be useful for incorporation in the IDSS and how these models can be coupled within the IDSS, e.g. because it was unknown what input these models need and what output they generate.

Hence, the purpose of the study was:

to give recommendations about the possible application of relevant models, available at the participating water boards, in the IDSS.

This will be done by:
1. giving an overview of the models that are used at the different project partners,
2. giving an assessment of these models with respect to their use in the nofdp project and their usefulness in the IDSS and
3. analysing the possibilities of model coupling for the aims of nofdp.

To reach this purpose in a well-considered way, some research questions were drawn up that, in turn, were subdivided into partial questions:

1. What subjects are relevant for the assessment of the usefulness of models in an IDSS?

1.1 What demands do end-users make upon the IDSS, so that it is easy for them to handle the IDSS?

1.2 How can it be assessed if models are adequate in terms of functionality and quality?

1.3 To what technical requirements do the selected models have to come up to get implemented in the IDSS?

1.4 What organisational demands are made upon the models to get implemented in the IDSS?

2. How are the models assessed according to these criteria?

2.1 What models are used at the different project partners?

2.2 What are the global information requirements of the IDSS?

2.3 What input does each model need and what output is generated by them?

2.4 How are the models assessed, when they are compared with the criteria that follow from the answer to research question 1.

3.What can be concluded from the comparison of the analysis results of the assessed models by means of their usefulness for the IDSS and the way in which they can be coupled with one another?

3.1 Which of the assessed models are useful to implement in the IDSS?

3.2 In what way should information flow through the IDSS?

3.3 What technical solution(s) should be used to couple these models with one another?

The study only accounts for qualitative aspects of model selection and coupling. In many other studies, uncertainty analyses were and are carried out so that the model that has the optimal complexity can be picked out. This is not necessarily the most complex or detailed model (De Kok and Wind, 2003; De Kok and Holzhauer, 2004, De Kok et al., 2004). Due to the large number of models to be evaluated, the time constraints of the internship and the demands of the project working group, these quantitative aspects were left out of consideration.

In addition, only models available at the four water boards participating in the nofdp project were evaluated. Of course, related to the overall target of nofdp, some types of models are missing. Those models have to be supplemented by the nofdp-development group at a latter stage of nofdp.

1.4 Layout of the report

This report is organised as follows. In chapter 2, a theoretical background will be given that contains an overview of the two most current approaches towards model selection and of the way in which model selection and coupling have been carried out in other DSS development projects. This analysis and the specific features of nofdp resulted in the approach towards the purpose of the study and in criteria with which the models are assessed. These can be found in chapter 3. After this chapter, research question 1 is answered. Chapter 4 tries to find an answer to research questions 2 and 3 by presenting the results of the selection process and giving some details about the scientific and technical aspects of model coupling. Finally, in chapter 5, recommendations for the project will be given together with a critical view on the approach and the results. Selected references, a glossary, a list of abbreviations and the appendices can be found at the end of the report.

2. Theoretical background

After the problem was made clear, an overview of the theory used to come to a research plan was made with the aim of getting a good scope of how the process of the selection and coupling of models had taken place at other projects and what recommendations were made for future projects. First, a short discussion about the two most valid approaches (top-down and bottom-up) in model selection will be given in sections 2.1 and 2.2. Linked to these approaches, in section 2.3, several other DSS building projects are discussed about how they have filled in their model selection processes. Next to this, the way in which qualitative model coupling has been carried out for other DSS is observed and reported in section 2.4. Finally, an end-note about the theory will be given (section 2.5).

2.1 Top-down approach

The design of the model base for the IDSS can take place in many different ways. In the attempt to make this design process as less as possible an ad-hoc process, it is very useful to reason out of a well-defined perspective. The two most often used perspectives are the perspective of the purpose of the DSS (top-down approach) and the perspective of the available models (bottom-up approach).

The top-down approach (see appendix A for a full description) can be very valuable, but has the disadvantage that it can only be applied to a constrained number of projects. Sometimes, the boundary conditions of the project can be such constraining that the top-down approach loses its value. Especially restrictions in the availability of models can force one to use another approach. Also when a *system diagram* is not yet available, there is no starting point for the model selection and a large part of the approach loses its worth.

2.2 Bottom-up approach

Although the selection of the models to be used depends on the purpose of the exercise and on the scale of the assessment, sometimes restrictions, as mentioned above, force one to base his choices on the data and model availability and accessibility (Salt et al., 1999). In such cases the bottom-up approach (see appendix B for a description), the opposite of the top-down approach, can be an outcome. According to McIntosh et al. (2000), it is even not necessary to have a clear purpose for the DSS when using a bottom-up approach.

This approach is more ad-hoc than the top-down approach and that is why this approach may not always be successful or efficient. The major requirements for the use of a bottom-up approach are a loosely defined purpose, complementary of available research and the permission of integration after *adaptation* or *rebuilding* of the models (McIntosh et al., 2000).

The major disadvantage of the bottom-up approach is that it is based upon models that are built to tackle a set of problems from a particular perspective and so cannot easily be integrated with other models without adaptation or rebuilding. That is why problems can be faced later on in the process when these models have to be coupled. To solve this problem, an iterative process of selection and coupling should be achieved.

2.3 Model selection at other DSS development projects

Although it is suggested that there exist no scientific standards to measure when it is appropriate to integrate models in a DSS and that this makes the design an ad-hoc process, especially when *statistical* and *dynamic models* are used in combination (De Kok et al., 2004), research done at other DSS development projects can deliver a good starting point for designing a research optic for the model selection for the IDSS. In this section, the comparison of the results of the analysis of four examples of model selection for former DSS development projects (WadBOS, Elbe-DSS, MODULUS and Great Lakes / St. Lawrence DSS) will be discussed. Descriptions of the selection and coupling processes for these projects can be found in appendix C.

When the selection processes of the projects are compared with one another, it can be seen that there are a few similarities:

- All projects use a combination of end-user, scientific, technical and organisational criteria for model selection.
- At all projects, the models are reviewed with model description forms that are compared with these criteria.

But when one has a closer look at the projects, it becomes clear that there are a lot of differences between the projects and that many of these differences are linked with one another:

- The model selection is not carried out at the same stage for all projects. The major reason for this are the differences between the top-down and the bottom-up approach for the design of the DSS. For the WadBOS and the Elbe-DSS projects, model selection was carried out when the function of and the demands for the DSS were clear. For the MODULUS project, there was no clear purpose, so that there had to be a well-defined list of demands for the DSS at first. For the Great

Lakes / St. Lawrence project, there was hardly a clear direction at all, so that just a first inventory could be made.

- For all projects, the type of source, from which models were chosen, differed. For the WadBOS project, as many domain models as possible were evaluated and sometimes models were made by the developers themselves. Also the Great Lakes / St. Lawrence project regarded as many models as possible, but because this was just an inventory, only existing models are incorporated. The Elbe-DSS and the MODULUS project both used models from other projects and hence, just a limited number of models could be used. This had the consequence that the selection process had to be an informal process and that many models had to be adapted or rebuilt.
- The three European projects made a DSS where the models were incorporated so that a selection could be made between models. In the Great Lakes / St. Lawrence system DSS, just the skeleton will be defined and the users have to ‘plug in’ the models themselves. This results in selection procedures with vast criteria for the European projects and an inventory of possible models with just key features for the Great Lakes / St. Lawrence project.
- Although most of the selection criteria are the same for all projects, some criteria differ for the projects. It has to depend on the purpose of the DSS which criteria should be incorporated. By no means, these criteria can be copied without keeping the purpose of the DSS in mind.
- For the Elbe-DSS and the MODULUS project, priorities were assigned with respect to the use of *freeware* and *open source* models. For the Elbe-DSS, financial restrictions were made (no commercial software) and it was demanded that models should be open source. When the functionality of the models was limited, the project team built its own models. The MODULUS project only adapted existing models from an identified group of EU-funded research projects, that made their models available for free. For the other two DSS, no financial restrictions could be found in the literature.

2.4 Qualitative model coupling at other DSS

The coupling of the different selected models is almost always related to the development of the system diagram in the early stages of the project. Sometimes, due to a lack of a well-defined system diagram or a lack of models to represent the system diagram straightforward, the models have to be structured in a different way. In this section, the (suggested) way of model coupling for the same four DSS projects as in section 2.3, extended with the EU-LIFE Dommel project is discussed. Details can be found in appendix C.

The differences between the top-down and the bottom-up approach result in a different process that will lead to the best way in which models should be coupled. When a top-down approach is used, a clear system diagram is already available and for each process in the diagram, the model that gives the best results when modelling this process can be selected and these models can be coupled with other models according to the diagram. When no system diagram is available, a so-called *information flow table* (IFT, see table 2-1) can give a good solution to define the 'ease of fit' for each sub-model and to define the best way in which models can be coupled. This table shows the types of information that will be collected (in the cells), how the information will be collected (left-hand column) and how it will be used (upper row). The purpose of the table is to ensure an appropriate flow of information in the correct sequence and to communicate to others how the information system functions.

Table 2-1: General information flow table (McIntosh et al., 2000)

From↓	To→	Sub-model a	Sub-model b	Sub-model c	Objectives
Sub-model a		xxxxxxxxxx			
Sub-model b			xxxxxxxxxx		
Sub-model c				xxxxxxxxxx	
Scenario parameters					xxxxxxxxx
Measures					xxxxxxxxx

Next to the functionality of the models, also technical possibilities can determine to what extent the selected models can be coupled. From nofdp meetings in Vught and Darmstadt, it became clear that the IDSS should have certain generality and flexibility and that existing models should be reused as much as possible. It was also suggested that users should be able to plug in their own models. State-of-the-art software technologies like *Component Based Development* (CBD*)* and *application frameworks* enable to develop information systems that use and integrate existing parts to a large extent. The integration effort does not stop with the delivery of the first prototype but is a constant activity during the whole lifecycle of the system. More details about CBD can be found in appendix D.

2.5 End-note

Although it may be suggested that model selection takes place either top-down or bottom-up, nearly always a mix occurs. When a project is said to use a top-down or bottom-up approach, it may have some characteristics of the other approach. For each project, the optimal mix has to be found.

3. Research method

With the theory about model selection and coupling that was structured in the last chapter, a method was developed that could serve as a tool for model selection and a first attempt to regard how the selected models can be coupled within the nofdp IDSS. The process of model selection and coupling was done bottom-up and the available models were the starting point of it (see figure 3-1), although top-down approaches are more current. There are three main reasons for this:

1. No well-defined system diagram was made at the moment of model selection. Just system diagrams of former DSS development projects could be taken as a reference.
2. The fact that no other models are evaluated than those provided by project partners, means that the selection process is constrained in the comparison of models with one another. When just one model was evaluated for an issue, it was given a positive advise when it met the selection criteria in an adequate way and when it fitted with other models. When the model does not represented the overall purpose of the project exactly, it had to be accepted. Hence, the approach could not be purpose-driven.
3. Straight integration, adaptation and rebuilding of the models are possible. So when a model fits the selection criteria, it can be implemented and the fact that it does not meet the *local* and *global information requirements* for 100% is no restriction for implementation.

Although the process was mainly bottom-up, as many top-down characteristics as possible were used as proposed in the literature (McIntosh et al., 2000). Bottom-up approaches at former DSS development projects like MODULUS (McIntosh et al., 2000) and the Great Lakes / St. Lawrence DSS (Great Lakes Commission, 2002) were taken as a reference.

By means of face-to-face interviews with open questions (the questionnaire can be found in appendix E and the list of interviewed persons in appendix F) at the participating water boards (Brabantse Delta, Aa en Maas and De Dommel in the Netherlands and Mümling in Germany), research institute TNO as developer of the Waterdoelen model that is in use at the province Noord-Brabant and engineering company Brandt-Gerdes-Sitzmann that runs a rainfall-runoff model for the Mümling catchment, an inventory of models was obtained that was processed according to a fixed pattern. By working with six interviews, a source triangulation was obtained, because partly the same models were discussed during those interviews. Finally, with literature research, the way of model selection and coupling at the design of other DSS was studied and the information about the models was completed.

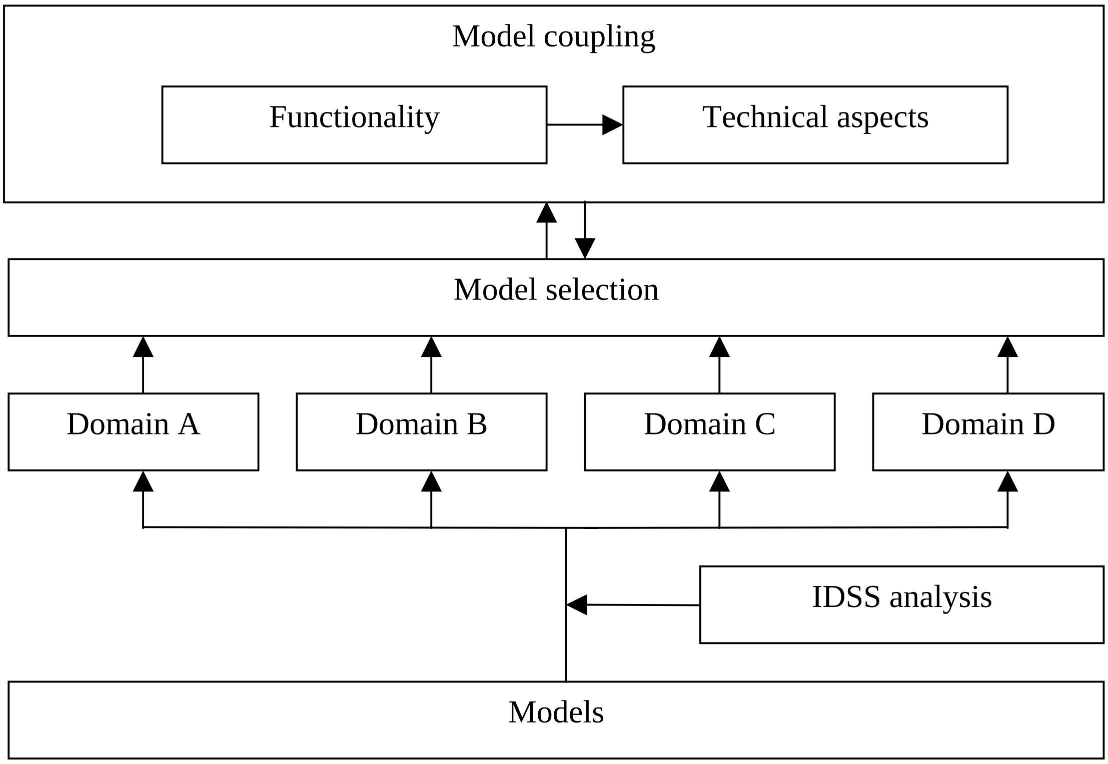

Figure 3-1: Research method

The models used by the four water boards formed the pool of candidates from which the models to be used in the IDSS would be selected. During the project, also other potential interesting models were faced and when they seemed interesting for the project, it was decided to evaluate them too, but not in too much detail, due to time constraints.

Prior to the processing of the obtained information, the requirements of the IDSS were analysed, due to a lack of a good system diagram at this stage of the project, with a strong focus on the end-users of the system. This analysis had to make clear what the important issues, measures, objectives and the optimal temporal and spatial scales are. After this, the reviewed models were ranked into different *application domains*. With the results of the *model description forms* (for details, see table 3-1 and appendix G), a selection procedure was carried out determining the usefulness of each model against a set of formulated *end-user*, *scientific*, *technical* and *organisational criteria* (appendix H) according to the ‘expected value method’ (Nijkamp et al., 1990). These criteria were generated out of criteria that were used at other DSS development projects and the special features of nofdp. The results formed the starting point for the iterative process between selection and coupling.

Table 3-1: nofdp model description characteristics

Model characteristic	Description
Addressed issues	Which issues are processed within the model? E.g. groundwater, hydrology, hydraulics, surface water quality or ecology.
Processes modelled	Domain processes explicitly modelled, e.g. seed dispersal, lateral volumetric water flow.
Class of models	Type of model, e.g. empirical, dynamic, stochastic, deterministic.
Model input	Inputs required to run.
Outputs generated	What output is generated by the model?
User possibilities	Can the system easily be used by the targeted end-users?
Modularity	Is the model composed of relatively independent *modules*? Can it be easily broken down into component pieces?
Temporal issues	Time-step length, time horizon and simulation run length.
Spatial issues	Is the model spatial or non-spatial? Can it be easily spatialised? How is it spatialised? What spatial scale does the model have?
Uncertainty	Assumptions and hypotheses explicitly or implicitly built into the model. Uncertainty in the model output.
Level of genericity	Is the model applicable only to a certain area or more generic?
Internal/External	Are the models run internally or by external consultants? Is the model built by own experts or externally? Does the water board have the owner rights of the model?
Development status	Is the model implemented, at the conceptual phase etc.?
Software code	Implementation language / open source.
Costs	Is the software for free or commercial? Are the required input data for free or is it necessary to pay for them?
Satisfaction	Are end-users satisfied with the use of the model? Do they think that the model can be of use for the nofdp-IDSS?

In the study of how to couple the *model components* with one another, they were evaluated for their functionality as components of the integrated nofdp-IDSS at first. All models were treated as a *black-boxes* and only the inputs needed and outputs obtained were regarded. The methods that a model itself uses to calculate variable values are irrelevant. To perform a useful function in a DSS, each model component should perform a task not carried out by any other model components and together they must operate in such a way that all local and global information requirements are satisfied. This was assessed with an IFT. After that, it was observed if the models could be integrated from a technical point of view. Here, two application frameworks were reviewed about there usefulness to couple the selected models. After the coupling study was carried out, its results were used to determine if the selection proposal was still valid. When this appears not to be the case, the second best model of the selection was taken and again it was determined if this model could be coupled with the other selected models. This iteration continued until an acceptable solution was found, that only contained models that can be coupled with one another.

4. Selection and coupling results

The results of the study, especially of the iterative process of model selection and coupling, are described in this chapter. As stated before, only models that are applied at the water boards participating in nofdp were observed. It will not be possible to construct the IDSS only with these models (e.g. because flood risk is an issue, economic models like flood damage functions are necessary), but in this chapter a suggestion will be given which models are the most suitable ones for implementation, what should be their position in the system and how they can be coupled.

In section 4.1, a short description of the way in which the models were evaluated and compared with one another will be given. Based on these model evaluations, a selection could be made that is described in section 4.2. After that, in section 4.3 a suggestion will be given about how the information should run through the system and which output can serve as input for other models. Finally, some technical details about the model coupling will be observed in section 4.4.

4.1 Model descriptions and comparisons

First, the models are sorted into five different domains, based upon the issues addressed by them and the subdivision that is made in the Handbook Good Modelling Practice (Van Waveren et al., 2000). Each domain represents an aspect of the integrated system that seems important to include in the IDSS:

- *Rainfall-runoff models*
- *Hydraulic models*
- *Groundwater models for the saturated zone*
- *Groundwater models for the unsaturated zone*
- *Water quality models*

For each domain, the model description forms (appendix F) were used to provide the information required for the evaluations. The information in the description forms was obtained by face-to-face interviews with developers and users of the models and by research of literature about the models.

Unfortunately, no *ecological models* were found at the water boards, though it is known that they exist. Examples of such models can be found in Verkroost et al. (1998) and Fuchs et al. (2003). Hence, these models are not evaluated in detail, but the rainfall-runoff, hydraulic, groundwater and water quality models are partly selected based upon how well they would fit with these ecological models.

Some models, that consist of different modules, can be used for different aspects of the IDSS. In those cases, the modules are evaluated separately and in some cases, different model description forms are filled in for the separate modules.

4.2 Selection of models

After the models were analysed, a *model selection* was carried out, where the term model selection means in this case: the process of assessing the models against the formulated end-user, scientific, technical and organisational selection criteria of appendix H for each model individually. This process is by itself a part of the iterative process of selection and coupling, so models that are selected as the most suitable model at first, are not the best models by definition. The definitive selection advise could be made after this iterative process.

First, in section 4.2.1, some thoughts will be made about the temporal and spatial scales that seem suitable for the two different levels of detail of the system to operate. After that, the results of the model selection are presented in section 4.2.2.

4.2.1 Temporal and spatial scales

To answer the questions the IDSS is faced with, it is very important that suitable spatial and temporal scales are chosen for the two levels of detail to represent the system being modelled. Spatial and temporal scales that are too high, result in too much detail and unnecessary precision. On the other hand, spatial and temporal scales that are too low, result in too little detail and the loss of interesting dynamics. The decision of which spatial and temporal scale to use should be influenced by the purpose of the IDSS and the nature and dynamics of the underlying processes. Figure 4-1 shows the characteristic temporal and spatial scales of the most important hydrological processes. The horizontal axes show the characteristic spatial scales and the vertical axes show the characteristic spatial scales. The yellow area includes precipitation, the green areas include flows over the surface and through water courses and the blue areas include groundwater flows in the saturated and unsaturated zone.

At the highest level of analysis, processes should be modelled, that are relevant at the scale of complete catchments (the right side of figure 4-1). At this level, models describing the impact of hydrology on runoff, large scale hydraulical models and water quality models should be incorporated. Time horizons at this level are in the order of magnitude of 10 to 100 years and many different temporal and spatial resolutions can be used (e.g. hours – years and 1 – 10 km).

At the second level of analysis, detailed models should be incorporated that describe the influence of flood damage prevention measures on nature conditions in the river, its banks and its floodplains (the left side of figure 4-1). At this scale, river sections of about 10 km long will be extensively studied and because of the large dynamics in such small areas, just small time horizons are relevant. Temporal and spatial resolutions at this level have to be high to model these dynamics in an adequate way (e.g. hours – days and +/- 10 m).

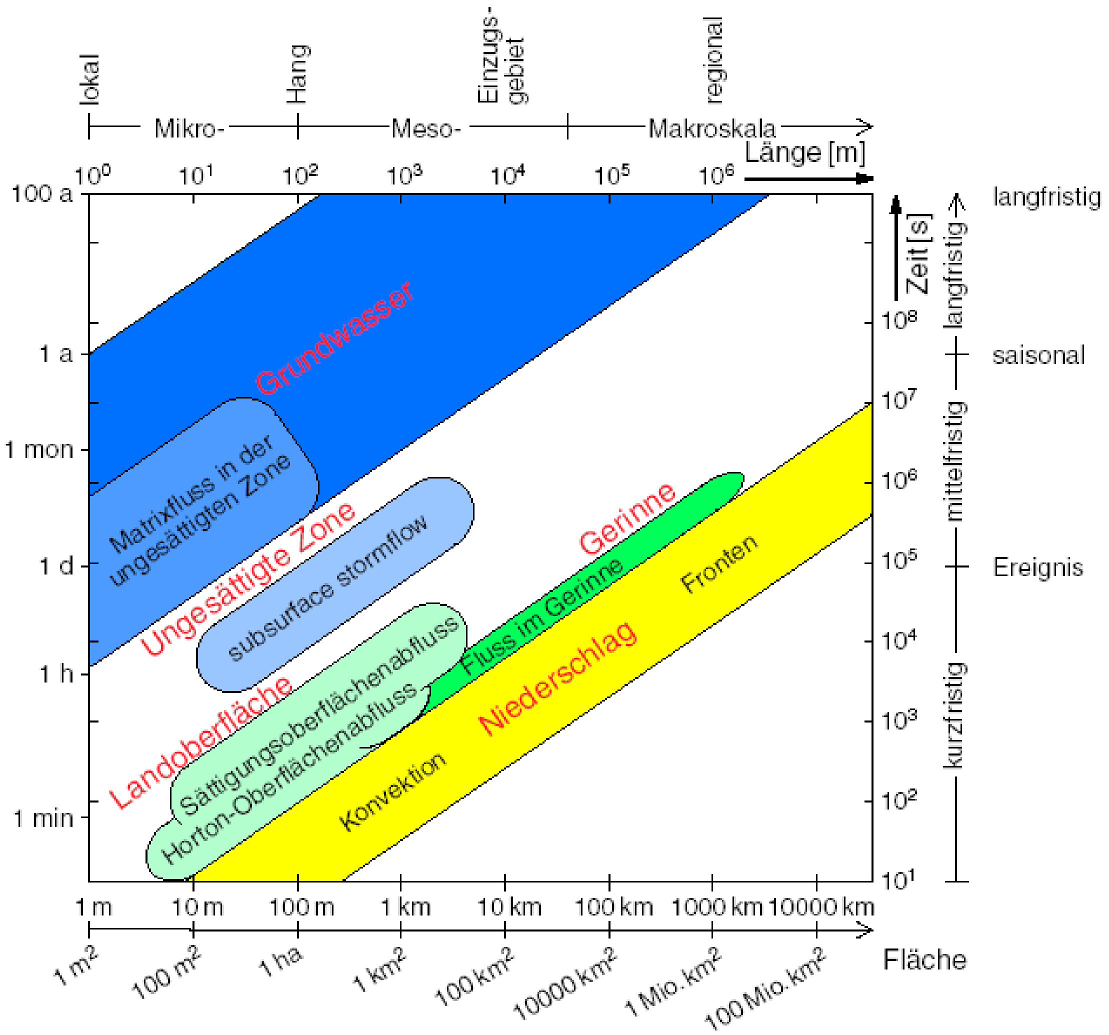

Figure 4-1: Characteristic spatial and temporal scales of some hydrological processes and working scales of the hydrologic modelling (Bronstert et al., 2001)

4.2.2 Selection results

As mentioned before, five different model domains were identified and a total of fourteen candidate models and modules were found at the water boards. Some types of models (rainfall-runoff models) had four candidate models and modules available for selection, while other types (groundwater models for the unsaturated zone and water quality models) had only a single candidate module. Where there was more than one candidate, the model selection was based upon the expected value method (see appendix I) after comparing the model description forms with the selection criteria. For the model domains that only had one candidate, this candidate was critically analysed concerning its internal suitability.

This section will describe the results of the model selection process for each type of model. The following details will be provided:

- The name of the model or module selected.
- The water boards that use the model.
- The reasons for the model or module to be selected.
- A brief description of other candidates.

A full description of the selection processes, including the scores for all models, can be found in appendix J.

Rainfall-runoff model

Module selected (long term):
DUFLOW Rainfall Runoff Module (RAM)
Used at water board:
Brabantse Delta
Reasons for selection:

1. End-user criteria:

- Processes: Only rainfall-runoff module that can model water quality.
- Genericity: Suitable for all types of areas.

2. Technical criteria:

- Flexibility: Easy to extract, adapt and develop.

Because DUFLOW will not be migrated to the OpenMI in the short term (see section 4.4.2), the second best model, SOBEK-RR, is suggested for implementation until it is clear if this will happen in the future. After this migration will have taken place however, DUFLOW-RAM should be implemented, because of the major advantage of simulating diffuse pollutant sources.

Module selected (short term):
SOBEK Rainfall Runoff (RR)
Used at water boards:
Brabantse Delta, Aa en Maas and De Dommel
Reasons for selection:

1. Scientific criteria:

- Scientifically proven: State-of-the-art model.

2. Technical criteria:

- Compatibility: Migrated to the OpenMI.

Other candidates:
HYBNAT:

- Models the fewest processes.

- Cannot be coupled with *GIS*-tools.
- No interfaces with other models that are evaluated.
- Property of engineering company.

SIMGRO:

- No water quality modelling.
- Long calculation times.
- Mainly suitable for the Netherlands.
- Coupling with SOBEK seems interesting.

Hydraulic model

Module selected:
SOBEK Channel Flow
Used at water boards:
Brabantse Delta, Aa en Maas and De Dommel.
Reasons for selection:

1. End-user criteria:

- Input: many modelling possibilities.
- User friendliness: calculates extensive flow networks in less time than DUFLOW.
- Satisfaction: users are very satisfied about SOBEK.

2. Scientific criteria:

- SOBEK fits all scientific criteria.

Other candidate:
DUFLOW water quantity:

- Less extensive and fast than SOBEK-CF.
- No migration to the OpenMI in the short term.

Groundwater model for the saturated zone

Model selected:
MODFLOW
Used at water boards:
Brabantse Delta and De Dommel.
Reasons for selection:

1. End-user criteria:

- All processes: can simulate *compaction* and *subsidence*.
- Input: uses common input values.
- Genericity: gives good results for all types of soils in all areas.
- Spatial issues: suitable resolutions.
- Satisfaction: preferred by water boards.

2. Scientific criteria:

- Spatial issues: suitable resolutions.
- Compatibility of scientific paradigms: *transient flow* assumed.

3. Technical criteria:

- Compatibility: migrated to the OpenMI.

Other candidates:

MLAEM:

- Needs some uncommon input data.
- Difficult to handle.
- Not suitable for local scale.
- Uses approach that is very different from that of other models.

SIMGRO:

- Has shortcomings on local scale.
- User unfriendly.

Groundwater model for the unsaturated zone

The unsaturated zone module of SIMGRO was evaluated for its suitability for implementation into the IDSS. This is a module that has its origin in a model that is used for regional policy making and not for the local scale on which ecological processes take place. Because a groundwater model for the unsaturated zone has to generate some of the major input variables for the ecological models (Fuchs et al., 2003), this is not desirable. It also does not count for *soil moisture* quality processes. A combination of a more detailed model for the unsaturated zone (e.g. the INFORM module WASBOD, see Fuchs et al. (2003) or MOZART, see Kroon et al. (2002)) and one that can model the quality of the unsaturated zone (e.g. SMART, see Pieterse et al. (1998)) would be preferable.

Water quality model

The water quality module of DUFLOW was evaluated for its suitability for implementation into the IDSS. After contact with some specialists in the field of model coupling, it became clear that it is almost impossible to couple this module with SOBEK-CF and that is why a choice has to be made between DUFLOW-quantity with DUFLOW-quality on the one hand and SOBEK-CF with a water quality model or maybe SOBEK-quality on the other hand. Because the latter options gives more possibilities for coupling with other models by means of the OpenMI, this option is preferred.

4.3 Information flow

Models in an integrated IDSS do not exist in isolation, but must interact with other models in such a way that each model receives the input it requires and produces output that is necessary to run other models. In this section, the input parameters demanded by each model are compared with the set of parameters provided by other models. The aim of this section is twofold:

1. To see how well the local information requirements of each model and the global information requirements of the total IDSS were met with the selected models.
2. To provide an overview of how information will run through the IDSS and to give an impression of the position of the selected models in the structure of the IDSS.

To assess the functionality of each model and the influence of scenarios and policy levers on parameters, an information flow table (see table 4-1) was constructed and completed by analysing to what extent the input requirements of the different models were satisfied by other models. Only the influence of scenarios and measures on the selected models and the functionality of output of the selected models for other models and for objectives were observed. So, the direct influence of scenarios and measures on, for example, ecological models was left out of consideration.

Because it is not clear at the moment which scenario parameters, measures, objectives and model domains will be incorporated into the IDSS, the relevant ones that were used for the Elbe-DSS (scenarios, measures, objectives and models) and INFORM (model domains) were assumed as preliminary parts of the IDSS to make the table complete. To determine which ones are relevant, the issues of concern for the IDSS were identified. Because the issues of the nofdp (nature-oriented flood damage prevention) project can be described as nature and flood damage prevention, scenarios, measures and objectives concerning those issues were incorporated into the scheme. Table 4-2 presents those scenarios, measures and objectives for both issues.

Table 4-1: nofdp IDSS selected models information flow table

	From↓ To→	Selected models: SOBEK-RR or DUFLOW-RAM	Selected models: SOBEK water quality	Selected models: SOBEK CF	Selected models: MODFLOW	Other models: Groundwater quality model	Other models: Unsaturated zone model	Other models: Ecological models	Objectives: Ecological improvement	Objectives: Flood risk reduction
Selected models	**SOBEK-RR / DUFLOW-RAM**		Concentrations (only DUFLOW)	Runoff	Recharge	Concentrations (only DUFLOW	Infiltration flux			
	SOBEK quality					Concentrations Loads		Saprobic state		
	SOBEK-CF	Water levels	Discharge Flow velocity Water depth		Surface water levels			Flow velocity Stream dimensions		Discharge
	MODFLOW	Exfiltration		Horizontal drainage		Groundwater level Specific discharge	Groundwater level	Groundwater level		
Scenarios	**Climatic changes**	Precipitation Evaporation								
	Land use changes	Land use								
	Socio-economic changes	Concentrations								
Measures	**Ecological oriented management**	Land use Features (un)paved area		Bed friction						
	Agricultural measures	Land use Features unpaved area Concentrations								
	Spatial planning	Land use Features (un)paved area								
	Dike height changes			Cross section						
	Dike replacements			Cross section						
	Retention areas			Shape of the network						

Table 4-2: Issues of concern, scenarios, measures and objectives used for the information flow table.

Issue	Scenarios	Measures	Objectives
Nature	Climatic changes Land use changes Socio-economic changes	Ecological oriented management Agricultural measures	Ecological improvement
Flood damage prevention	Climatic changes Land use changes	Spatial planning Dike height changes Dike replacements Retention areas	Flood risk reduction

An example of possible coupling points between the rainfall-runoff, the hydraulic and the groundwater model are shown graphically in figure 4-2. For each sub-catchment, a rainfall-runoff model can be developed, that calculates the runoff out of the precipitation that is measured at the yellow spots and passes it to the SOBEK-CF model at the orange spots. The SOBEK-CF models with a low resolution are coupled with one with a high resolution at the green spots. This high resolution model calculates water levels at the red spots that are passed to the MODFLOW model that is developed for the grid. The information flows between the different models are explicated below the figure.

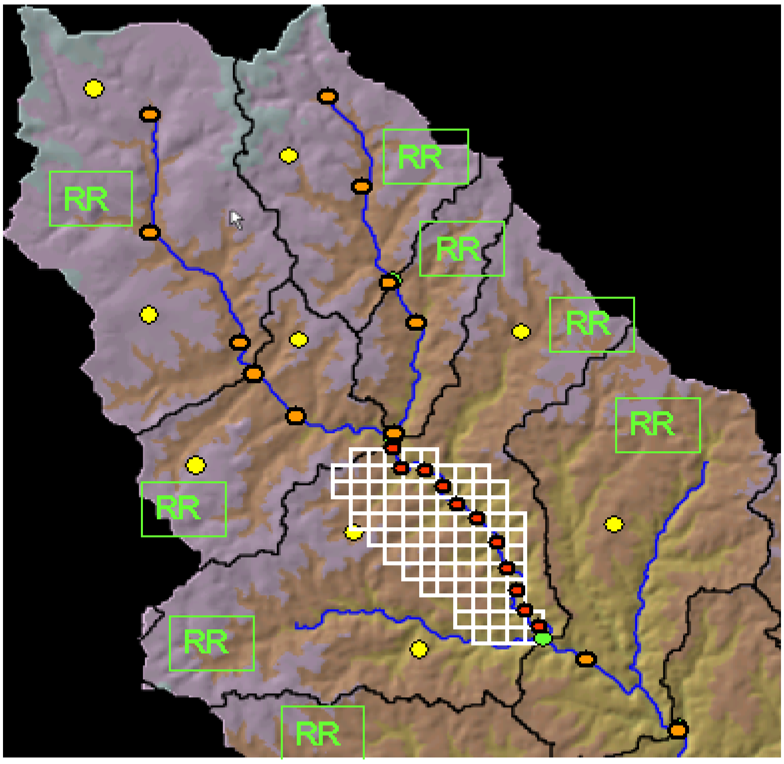

Figure 4-2: Coupling points between different models (Blind and Gregersen, 2004).

Rainfall-runoff model and SOBEK-CF

The rainfall-runoff model (SOBEK-RR or DUFLOW-RAM) has to provide SOBEK-CF with its runoff that can serve as lateral inflow or as upper boundary. SOBEK-CF can provide the rainfall-runoff model with its calculated water levels that can serve as lower boundary. This is an iterative process that may take some time, but should be easy to perform with the OpenMI.

Rainfall-runoff model and MODFLOW

Also between the rainfall-runoff model and MODFLOW, an iterative process takes place. The rainfall-runoff model computes the *recharge* as the *percolation* minus the *capillary rise* and the horizontal drainage. The groundwater component in turn, calculates the *exfiltration* as the recharge minus the *phreatic storage coefficient* times the change in groundwater level during the time step. Recharge and exfiltration are exchanged until the exfiltration is stabilised. (Gijsbers and Brinkman, 2004)

Rainfall-runoff model and SOBEK-quality

Only when DUFLOW-RR is used, the rainfall-runoff model can provide the water quality model (SOBEK is assumed) with calculated inflow concentrations due to *diffuse pollutant sources*.

SOBEK-CF and MODFLOW

SOBEK-CF has to provide MODFLOW with surface water levels. MODFLOW in turn, has to provide SOBEK-CF with the horizontal drainage, based on the difference in groundwater and surface water level and the *soil resistance*. (Gijsbers and Brinkman, 2004)

SOBEK-CF and SOBEK-quality

The channel flow module provides the quality module with the discharge, flow velocity and water depth. These modules have to be coupled outside the OpenMI.

SOBEK-CF models with a high and a low resolution

The data flow between a SOBEK-CF model component with a high and one with a low resolution is not reflected in table 4-1, but these models have to calculate the boundary conditions of one another. The upstream model has to calculate its outflow that is the upper boundary condition for the downstream one. The downstream model in turn, has to calculate its upstream water levels, that can serve as lower boundary condition for the upstream model.

Groundwater quality model

To determine the information requirements of the groundwater quality model, the future INFORM module GRUNDQUAL was taken as example. Of the parameters that can be calculated by the proposed models, this module needs data of the catchment (as provided by DUFLOW-RAM), water quality data of the surface water (as provided by SOBEK-quality) and data about the groundwater quantity situation (as provided by MODFLOW).

Unsaturated zone model

To determine the information requirements of the model for the unsaturated zone, the model SMART2 was taken as example. Quantitative parameters that this model needs are the average spring groundwater level (as provided by MODFLOW) and the infiltration fluxes towards the unsaturated zone (as provided by the rainfall runoff model). This can be both seepage from the groundwater and infiltration from the atmosphere. Both fluxes are taken together as ‘infiltration flux’ in table 4-1.

Ecological models

The examples that were used for the determination of the information requirements of ecological models are the ones that were used for the Dommel DSS, i.e. Alnion, Move and Ecostream. Characteristic input parameters appeared to be groundwater level for woodlands and grasslands and saprobic state, flow velocity and stream dimensions for aquatic ecosystems. These can be delivered by MODFLOW (groundwater level), SOBEK-quality (saprobic state) and SOBEK-quantity (flow velocity and stream dimensions).

Objectives

With the selected models, no direct influences on the ecological state can be calculated, only indirect influences which need to be processed to information that is suitable for ecological models. For the objective ´flood risk reduction´, SOBEK-CF can deliver the discharges that only need to be processed to the critical discharge, probability of occurrence, damage when that discharge occurs and at the end to the flood risk. This last parameter can be calculated in a simple way as e.g. has been done for the Elbe DSS:

$$R = \int_{Q_{crit}}^{\infty} dq \; f(q) S(q) \qquad (4.1)$$

with R the risk, Q_{crit} the so-called critical discharge above which flooding will take place, f(q) the possibility that certain discharge q occurs and S(q) the damage when that discharge occurs.

Before the core of the IDSS structure could be drawn, it was observed for each model if it only seemed suitable on a catchment or local scale or that it could be applied on both scales. Out of the model description forms and the needs of both scales, it followed that DUFLOW-RAM and the SOBEK modules (except of SOBEK-CF) seemed more appropriate on the catchment scale, that MODFLOW was only necessary on the local scale and that SOBEK-CF could be applied to both scales. In figures

4-2 and 4-3, the suggested cores before and after migration of DUFLOW to the OpenMI are drawn together with the arrows from or towards *scenarios* (green arrows), measures (blue arrows) and objectives (red arrows). For the detailed contents of all the arrows, the reader is referred to table 4-1.

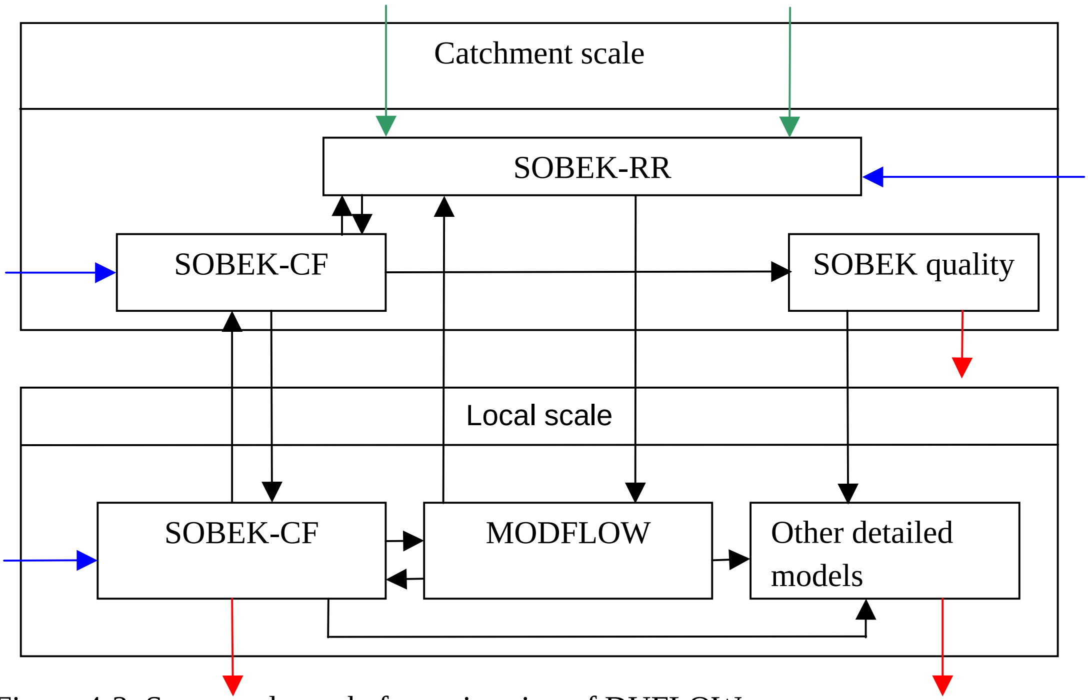

Figure 4-3: Suggested core before migration of DUFLOW

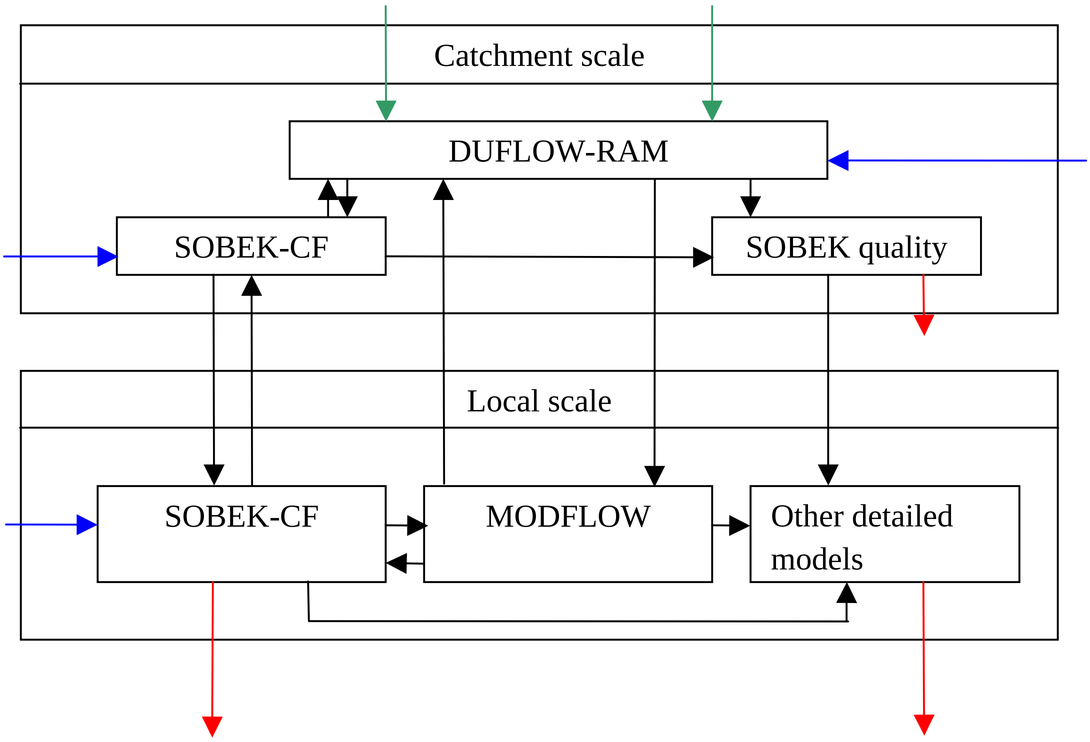

Figure 4-4: Suggested core after migration of DUFLOW

4.4 Coupling of the models

After the question is answered *which* models should be coupled, another question arises, i.e. *how* to couple these models. As mentioned in section 2.4, common software engineering methods to assemble software applications from components from a variety of sources are Component Based Development (CBD) and application frameworks, that are based on CBD. In sections 4.4.1 and 4.4.2, two examples of application frameworks, that seem interesting for coupling SOBEK, MODFLOW and DUFLOW, are discussed and compared with one another on their appropriateness to support the development of the IDSS.

4.4.1 Generic Framework Water

The Generic Framework Water (GF) is an open framework for linking models and creating DSS that has been developed by a large consortium of Dutch companies, like RIZA, STOWA, Alterra and RIVM. The purpose of the framework is to link all types of models relevant to integrated catchment modelling and potentially environmental modelling in general. It should be possible to couple the following models with the GF:

- DUFLOW
- MODFLOW
- SOBEK. Unfortunately, this is the River version, instead of the Rural version that is used at the water boards.
- SWAP. A model for the unsaturated zone.

Inside the GF, the following components are distinguished (Van der Wal, 1999):

- *Framework*. Container for framework components.
- *Process chain management tool (PCMT)*. With help of the PCMT, relations between model applications mutually and between model applications and generic tools can be defined. After that, the PCMT will take care of the sequence in which model applications and tools are handled.
- *Generic tools*. Tools that are responsible for general tasks. Examples are editors, graph tools and analysis tools.
- *Model applications*. These consist of a model engine that is *wrapped* so that other components of the GF can address the model engine.
- *Data Engine*. This manages the data or the reference towards data of all the GF components.

Figure 4-5 illustrates the co-operation between these components.

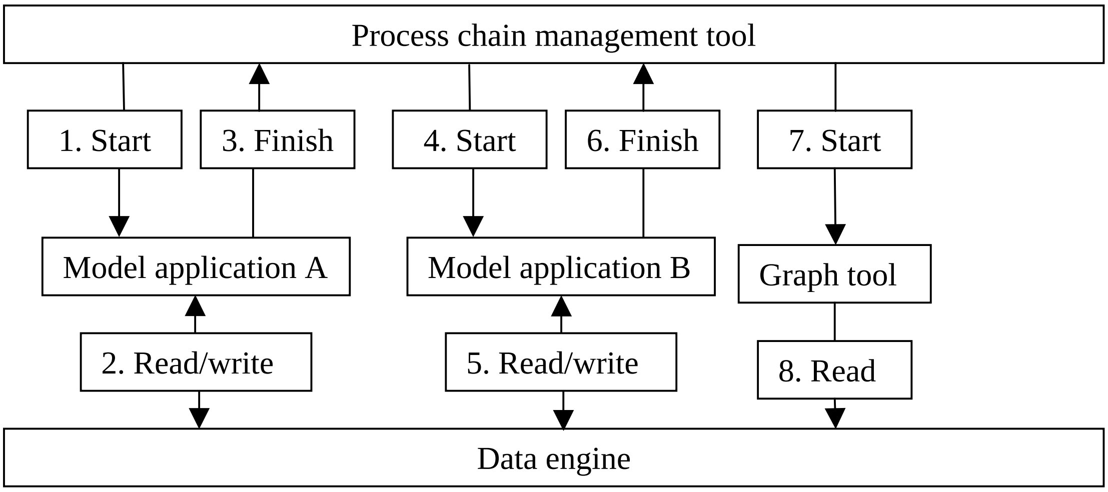

Figure 4-5: Co-operation between components in the GF (Van der Wal, 1999).

The GF offers some possibilities to overcome the differences in temporal and spatial scales. The user can manually define points of spatial linkage. No standard referencing system is imposed. To overcome problems with temporal resolutions, the GF exchanges the last calculated value of the requested model as input for the requesting model.

This form of overcoming scaling problems has some disadvantages. If two models with different time steps are linked, some form of buffer is required to store data from one model until it is valid (in terms of time reference) for use in the next model. Furthermore, depending on the numerical method used by individual domain models, time-steps of t-1, t, and/or t+1 (or more complex variations) may be used for computations at time step “t”. This type of linkage cannot be handled in the GF. The final scaling problem is the fact that a model calculates output for other moments of time then those for which it gets input, causes a source of uncertainty. Other disadvantages of the GF are the fact that linkages between models have to be implemented manually and that it is not possible to simulate iterative loops between models. Finally, a coupled system cannot be carried out without the, user unfriendly, graphical user interface (GUI) of the GF. This may be a problem when end users will work with the IDSS.

The GF will not be developed further, because it underlies a European counterpart, the "Open Modelling Interface" (OpenMI) of the HarmonIT project. This interface tries to solve the problems that were mentioned with the GF and so will be much more suitable for the IDSS. It will be discussed in the next section.

4.4.2 Open Modelling Interface

The purpose of the Open Modelling Interface (OpenMI) is to allow catchment process interactions to be represented in the formulation and selection of sustainable policies for catchment management (Blind and Gregersen, 2004). It resolves a number of complicated linkage issues, such as differences in spatial and temporal scales and feedback loops. The OpenMI standard is almost finished and in December 2004, the so-called ‘proof of concept’ started, for which non-insiders are transferring components to the system. The migration of the models and the implementation of the software environment is planned for March 2005 (Moore and Tindall, 2004). At the moment, RIZA has plans to implement a ‘DSS’, which means a coupled system of the models AGRICOM and MOZART, in the OpenMI with a humble GUI that can manage the input to both models by the standard interface.

In figure 4-6, a graphical representation is given of the models that will be migrated to the OpenMI the next few months. Of these models, especially SOBEK RR (defined as RR-WL), SOBEK-CF and MODFLOW seem interesting. Next to this development, the developer of DUFLOW, Mx.Systems, will investigate the possibilities to migrate DUFLOW to the OpenMI.

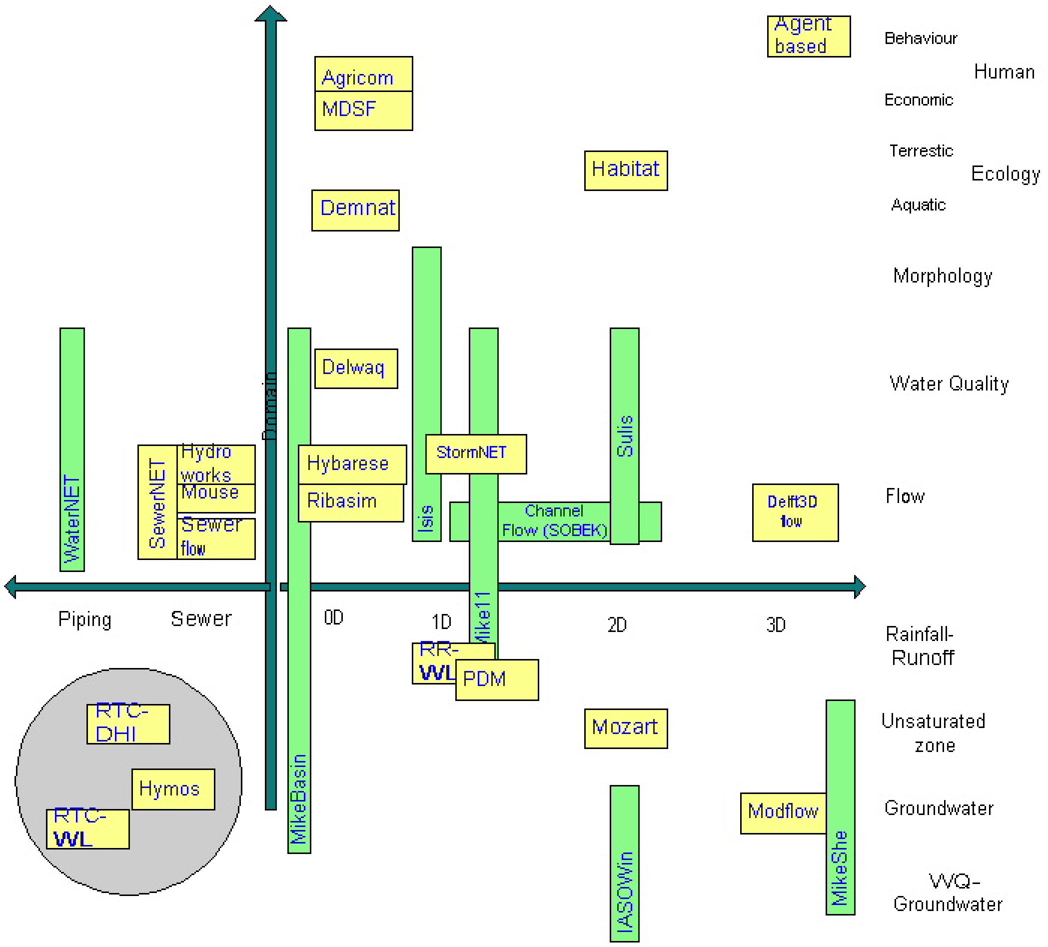

Figure 4-6: Models to be migrated to the OpenMI (Moore and Tindall, 2004)

When models are migrated to the OpenMI, the model engine is embedded in a so-called wrapper (the blue parts in figure 4-7), that supports the communication between the models and the OpenMI. The key to data exchange is the *'GetValues' method*. This mechanism is pull driven, meaning that a model that requires input asks a providing model for a value set for a given time at a set of locations (the interrupted arrows in the figure). The providing model calculates the required values and returns them (the regular arrows in the figure). This method is also used when getting data during initialisation of a model or retrieving data from databases.

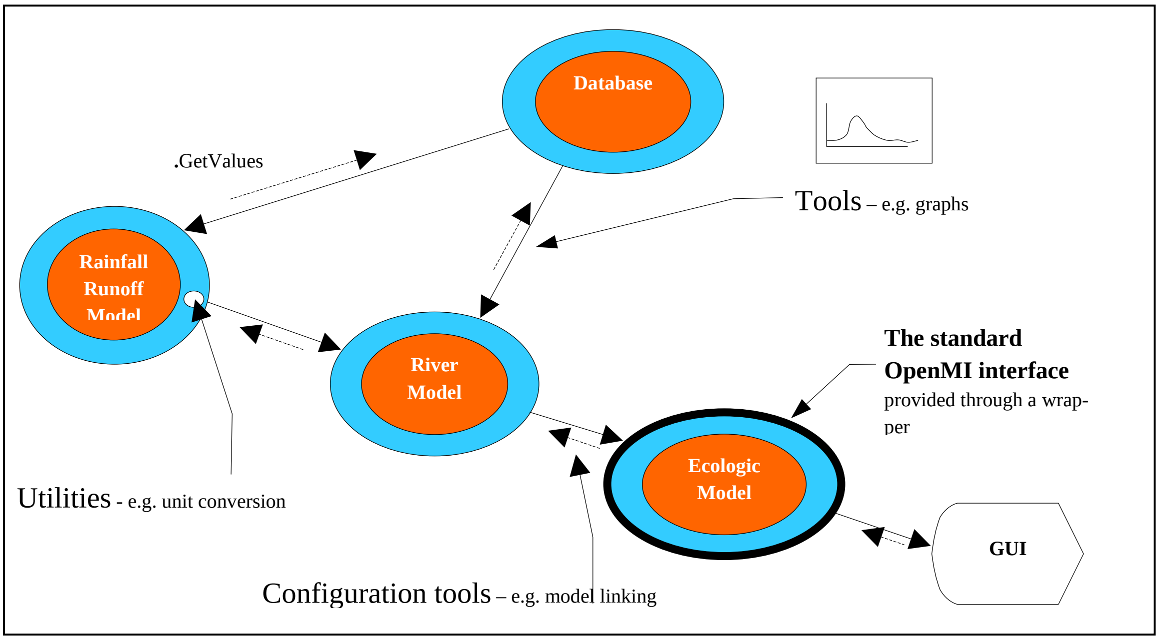

Figure 4-7: Facilities for wrapping, linking and running models (Gijsbers and Moore, 2004)

Models are allowed to perform the calculations at their own temporal and spatial resolution, but the GetValues mechanism requires that output can be delivered at any given time and place (Blind and Gregersen, 2004). To make this possible, an extendable library of *interpolation* and *extrapolation* functions is provided. When the requested model is asked to calculate a value, it:

- Start calculations, if the required time step has not been reached, but can be computed.
- Extrapolate in time if the required time step cannot be reached.
- Search its buffer if the requested time step has passed.
- Interpolate between different time steps if the requested time step does not match the internal time stepping.
- *(Dis-)aggregate* in space and time, if the requested spatial and temporal resolution does not match the internal resolution.

With respect to the GF, some major improvements are carried through in the OpenMI. The OpenMI delivers a GUI that supports the coupling of models, but that is not necessary to build up or run a coupled system. Hence, models can be built up in their own environment and transferred to the OpenMI afterwards. The OpenMI also provides the possibility of iterative coupling, so that interactions between e.g. groundwater and surface water can be studied. The way of dealing with different temporal and spatial resolutions is also improved. Finally, the automatic linking between models makes it more user friendly.

Hence, to support model linking, the suggestion is made to use the OpenMI instead of the GF. It will simplify the process of coupling models of different processes, spatial representations (1D, 2D, 3D), resolutions and models that use different units or that are based on different concepts. On the short term, DUFLOW and SOBEK-quality are not migrated to the OpenMI, so that coupling these components with SOBEK-CF has to be done outside the OpenMI. Because this is undesirable, it had influence on the model selection (see section 4.2.2).

4.5 Sub-conclusion

The participating water boards use a wide range of rainfall-runoff, hydraulic, groundwater and water quality models. Details about these models can be found in the model description forms. With an iterative process between model selection and model coupling, the choice was made to suggest a core of the model base of the IDSS that consist of SOBEK-RR, SOBEK-CF, SOBEK-quality and MODFLOW on the short term and with DUFLOW-RAM instead of SOBEK-RR after migration of DUFLOW to the OpenMI. An application framework like the OpenMI can support the coupling process.

5. Conclusions, recommendations and discussion

This final chapter consist of a number of conclusions and recommendations for a feasible design of the model base of the nofdp IDSS. These recommendations address the models that are recommended for implementation and a suggestion about the way in which the technical integration of the models should be handled in the IDSS. Finally, it will be discussed to what extent the approach and the results are valid.

5.1 Model selection

The study was committed to the reuse of existing models, so the model selection process was based mostly upon the existing form and function of the available models rather than a top-down purpose-driven approach. Hence, the approach employed to the model selection was bottom-up in character, although top-down approaches are more current in other projects. Following the bottom-up approach, the suggestion was made to implement five successfully evaluated modules chosen during an iterative process between model selection and model coupling. This process should provide the nofdp IDSS with a set of suitable models that can fulfil the global and local information requirements of the IDSS after some adaptation. Table 5-1 details the models that were suggested for implementation in the IDSS based upon the results of the iterative process.

Definitions used for selection status:

- Evaluated: model selected for use after comparison against other models of the same domain from contributing projects based upon end-user, scientific, technical and organisational criteria.
- Unevaluated: recommended as part of the nofdp IDSS due to a lack of suitable candidate models used at the participating water boards.

Table 5-1: nofdp model selection results

Domain	**Model recommended**	**Used at**	**Selection status**
Rainfall-runoff	SOBEK-RR (short term)	Aa en Maas Brabantse Delta De Dommel	Evaluated
	DUFLOW-RAM (long term)	Brabantse Delta	Evaluated
Hydraulics	SOBEK-CF	Aa en Maas Brabantse Delta De Dommel	Evaluated
Water quality	SOBEK-quality	-	Unevaluated
Groundwater	MODFLOW	Brabantse Delta De Dommel	Evaluated

5.2 Model coupling

Balancing the output generated and the input required by the selected models has allowed to design a structure for the core of the model base of the IDSS, consisting of model components (see figure 5-1). In this figure, the green arrows reflect input from external scenarios, the blue arrows reflect the possibilities to simulate measures, the black ones reflect the data flows between the models and the red ones reflect the influence on objectives in terms of ecology and flood damage prevention. For details about the contents of the arrows, the reader is referred to section 4.3. The typical resolutions at which the catchment layer vary from hours to years and 1 – 10 km. The typical resolutions at which the local layer should run are hours – days and +/- 10 m.

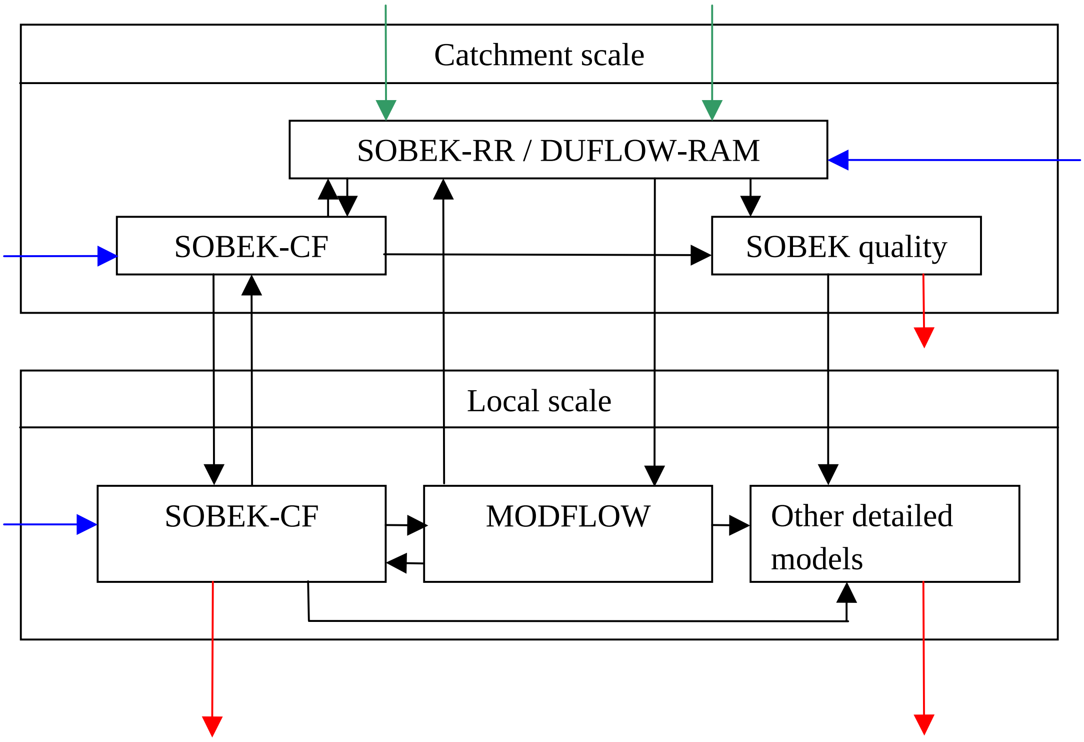

Figure 5-1: Suggested way of integrating components in the nofdp IDSS.

For the nofdp IDSS, reuse of models is desired. Different water boards have their existing models, that were originally developed as stand-alone models in different programming languages. To provide maximum flexibility and maximum possibilities for reuse, it is suggested to integrate the material on the basis of an application framework like the OpenMI. The OpenMI provides a sufficient and well-defined set of interfaces, that allows for the reuse of existing models which are available for the creation of DSS.

5.3 Discussion

The use of a bottom-up approach for the design of a DSS, whilst in this case necessary due to the aim of reuse and the lack of a system diagram, may not always be successful or efficient. Models are built to tackle a set of problems from a particular perspective and as such are not designed for integration with other models. Top-down approaches have been applied to many environmental management problems and provide a good template for the design of integrated decision making models (McIntosh et al., 2000). In the future, projects as nofdp should first make a clear delimitation so that the model selection and coupling process can take place more goal-directed.

Next to the approach towards the model selection, the results of the selection should also not be accepted uncritically. It is questionable to what extent the list of models and the information about them is complete. During the process, some (mainly ecological) models were faced that should be available within the water boards but were left unnoticed during the interviews that were held to get an overview of the available models. Due to time constraints these models were not investigated in too much detail, but were only used to judge if other models were good suppliers for e.g. ecological models. It is also likely that the information about the models is not 100% complete or correct. During the interviews, different answers were obtained on the same question and when exploring the literature to check which answer was correct, a third possibility showed up. In such cases, common sense was used to ‘select‘ the ‘right‘ answer.

It is also not clear in which way the selected models will be integrated into the IDSS due to the fact that no system diagram is available at the moment. The one used for the Elbe-DSS seemed suitable and was assumed to be valid so that the information flow table could be designed and an overview of possible functionality of the models for the IDSS could be obtained. Due to changing insights about e.g. ecological aspects and to the fact that nofdp has other priorities then the Elbe-DSS project, this diagram could be (partly) invalid and so, models that seemed to fit in the IDSS may not fit anymore. This, in turn, influences the selection process. This problem can be overcome with the use of a top-down approach.

Another source of uncertainty for the selection results is the subjectivity about the order of importance of the selection criteria. When a different order of importance is used, other results will be obtained. Based on recommendations of other DSS development projects, the priority was set to the end-user end scientific criteria. When this priority is moved to the use of freeware and open source models, i.e. the organisational criteria, non-commercial models will be given more priority. The results of such a priority shift were calculated and it appeared that SOBEK would lose its value because of its commercial status and the fact that it is not open source. In that case, it would be better to replace the SOBEK modules by their DUFLOW counterparts. When the use of freeware would be a clear restriction, the only option would be to use SIMGRO as a rainfall-runoff model. Hence, it is recommended to make clear agreements about priorities with respect to models.

It is assumed that for both scales of detail in the IDSS, the same hydraulic model will be used. On the catchment scale however, a coarser model than SOBEK-CF could also be sufficient. Hence, instead of SOBEK-CF, the rainfall-runoff model could be used to model flows on this scale. This results in the fact that SOBEK-CF would only be necessary on the local scale if such an approach is followed.

One may think by reading section 4.4.2 that all problems that were faced with model coupling in the past, can be solved with the use of the OpenMI. This is, however, absolutely not the case. In their evaluation of the use of application frameworks, Van der Meulen et al. (2000) mention two major problems:

1. Using an application framework is a technically complicated option as it became clear that converting existing models so that they can be reused in a component based simulation framework is often more costly and time consuming than programming the models anew. Hence, it takes professionally trained people to apply the software effectively. This has the great disadvantage known as the ‘Modelling Gap’: the model developer becomes dependent on the technician, and since the software code is intractable to him, he tends to get isolated from the running version of his model. Hence, a tight link between the model developer and the software technician is required.
2. It also became clear that the flexibility of the architecture was at the expense of the possibilities to change the models themselves. Flexibility was badly missing when changes were needed in the software components or in the data flows between them. Nearly every change made to a model changed the data flows between the models and required a change in the interfaces linking it into the integrated model. The consequent is that most problems occur when models have to be integrated that are not finished or existing ones that have to be changed to be coupled to one another in a scientifically correct and meaningful manner. Hence, the advise is given to make the components themselves ready to be plugged together at first and to implement them afterwards.

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Glossary

Adaptation	Keeping models in their original form but adapting the code in minor ways to meet the end-user requirements more successful
Aggregation	Multiplying calculated parameter value with the relative scale difference between models
Algorithm	The way in which a model processes its information
Application	Entire software system that one installs on his computer
Application domain	Partial area of water management
Application framework	Open system that leave the end-user of a DSS some choice which models to use
Black-box	Model in which only its externally visible behaviour can be considered and not its implementation or "inner workings"
Bottom-up selection	Model-driven way of selecting models
Boundary conditions	Parameter values at the boundary of a model
Capillary rise	Movement of water from the groundwater to the soil moisture due to capillary forces against the gravity
Catchment	Area that is drained by one and the same river
Compaction	Change in soil structure that causes a downward movement of the soil surface
Component	Software part, designed according to pre-defined specifications
Component Based Development (CBD)	Software engineering method that creates, integrates and reuses components of a program code
Data base	DSS component containing the raw and processed data of the domain and the area at study
Decision Support System (DSS)	Information system that supports decision making

Deployment	Physical executable file that is used to make the component run
Description	Information that a component furnishes about itself to allow consumers to understand it
Diffuse pollutant source	Source of pollution that stretches over a large area
Disaggregation	Dividing calculated parameter values by the relative scale difference between models
Domain	See *application domain*
Dynamic model	Model for which time is an independent variable
Ecological model	Model that simulates the influence of water on flora or fauna species
Encapsulation	Process of hiding the implementation or code that drives a component
End-user criteria	Criteria that follow answers to questions as: what is useful to be integrated with the end-users in mind?
Exfiltration	Outflow of groundwater
Extensibility	Possibility to extend the range of services of a component without affecting consumers
Extrapolation	Estimation of parameter value beyond calculated values
Flexibility	Ease with which a system can be adapted or changed
Framework	Container for components
Freeware	Software that is provided without charge
Generality	Possibility to use a system for other purposes than its original purpose
Generic Framework Water (GF)	Open framework for linking models and creating DSS
Geographic Information System (GIS)	Tool that combines layers of information about a place to give a better understanding
Get Values method	Method with which a model that requires input asks a providing model for a value set for a given time at a set of locations
Global information requirements	Required system inputs and outputs as determined by the overall purpose of the DSS

Groundwater model for the (un)saturated zone	Model that simulates flows of groundwater and/or soil moisture
Hydraulic model	Model that simulates water flow
Implementation	Code that makes a component work
Information and Decision Support System (IDSS)	Decision Support System that contains a knowledge base; in the report it always refers to the nofdp IDSS
Information Flow Table (IFT)	Table that shows the types of information that will be collected, how the information will be collected and how it will be used
Input	Data that a model become
Integrated River Basin Management (RBM)	Process of co-ordinating land and water within a river basin, in order to maximise both economic and social benefits
Interface	Boundary across which two systems communicate
Interpolation	Estimation of parameter value between two calculated values
Knowledge base	IDSS component containing information for riverine planning
Local information requirements	Information required by models to perform their function(s)
Model	Schematic representation of reality
Model base	DSS component containing relevant models
Model component	Component of a DSS that can be classified as model
Model description form	Form that details a candidate model
Model engine	Part of the model where calculations take place
Model selection	Process of assaying models against formulated selection criteria
Module	Independent part of a model
nofdp	Project that addresses integrated river basin management by providing support to decision-makers
Open Modelling Interface (OpenMI)	Application framework that provides standard interfaces for model coupling
Open source	Software of which anyone can copy the source code and modify it freely
Output	Data that a model generate

Organisational criteria	Criteria which have to test the models for their organisational availability for the project
Percolation	Downward movement of water through the soil
Phreatic storage coefficient	Measure for subterranean storage
Rainfall-runoff model	Model that simulates regional groundwater flow and water levels in the surface water
Rebuilding	Complete rebuild of a model for incorporation into a DSS
Recharge	Replenishment of groundwater naturally by precipitation or runoff, or artificially by spreading or injection
Replaceability	Property that makes it possible to replace one component with another
Reusability	Possibility of using a code developed for one application program in another application
Scenario	Possible future situation
Scientific criteria	Criteria that deal with what can and what cannot be integrated from a scientific point of view
Scientific paradigm	Assumption or representation of reality that underlie a model
Software code	See *source code*
Soil moisture	Ability of a soil to hold water
Soil resistance	Ability of soil to keep out water
Source code	The form in which a computer program is written by the programmer
Spatial resolution	Number of calculations per unit of distance
Spatial scale	Distance between calculation points
Statistical model	Model that can simulate randomness
Subsidence	Sinking down of a part of the earth's crust, generally due to underground excavations
System diagram	Diagram that represents relations between issues
Technical criteria	Criteria that assess if models can be integrated into an efficient operating IDSS
Temporal resolution	Number of calculations per unit of time
Temporal scale	Time between calculations
Tool base	DSS component containing methods, ana-

	lytical techniques and software required to work in an effective manner
Top-down selection	Purpose-driven way of selecting models
Transient flow	Flow for which the rate of fluid that flows through a system is not constant
User interface	DSS or model component enabling easy interaction between the user and the model
Water board	Authority concerned with the management of a catchment
Water Framework Directive	Governmental framework intended to address integrated river basin management
Water quality models	Models that can simulate the chemical quality of water systems
Wrapper	'Shell' in which a model engine is embedded

List of abbreviations

AGRICOM	AGRIcultural COst Model
BfG	German Federal Institute of Hydrology
CBD	Component Based Development
CF	Channel Flow
DSS	Decision Support System
EU	European Union
GF	Generic Framework Water
GIS	Geographic Information System
GUI	Graphical User Interface
HarmonIT	Information technology framework for water modelling
HYBNAT	Hydrologic Calculation of the Rainfall-Runoff-Transport Process
IDSS	Information and Decision Support System
IFT	Information Flow Table
INFORM	INtegrated FlOodplain Response Model
LIFE	Financial Instrument for the Environment
MLAEM	Multi Layer Analytic Element Model
MODFLOW	MODular three-dimensional finite-difference groundwater FLOW model
MOZART	Model for the unsaturated zone for national analyses and regional applications
nofdp	nature-oriented flood damage prevention
NWE	Northwest European
OpenMI	Open Modelling Interface
PCMT	Process chain management tool
RAM	Rainfall-Runoff Module
RBM	River Basin Management
RIVM	Dutch National Institute for Public Health and the Environment
RIZA	Dutch Institute for Inland Water Management and Waste Water Treatment
RR	Rainfall-Runoff
SIMGRO	SIMulation of GROundwater flow and surface water levels
SMART	Simulation Model for Acidification's Regional Trends
STOWA	Dutch Foundation for Applied Water Research
SWAP	Soil, Water, Atmosphere and Plant
TNO	Applied Physical Scientific Research
WadBOS	Wadden Sea Decision Support System

Appendices

Contents of appendices

Tables

Figures

Appendix A: Top-down approach

When a top-down approach is used, one starts with a top level view of the system and recursively decompose it into manageable pieces. According to the end-user requirements, a tightly defined purpose is defined at first and after that, the abstraction level of the process is lowered as it proceeds (De Bruin and Van Vliet, 2000). Successful examples of top-down approaches can be found in Holling (1978), Engelen (2000) and Matthies et al. (2003). Top-down approaches are also proposed by Donnelly et al. (1998), McIntosh et al. (2000) and De Kok and Wind (2002), who suggest that the most important part of any modelling exercise is the insight into the functioning of the system as a whole. It should be this insight which allows the modeller to select between alternative models.

The basis of the top-down approach is that a structured problem-solving strategy (Hall (1968), De Leeuw (1974), Mintzberg et al. (1976), Simon (1977), Ackoff (1981), Checkland (1981), Miser and Quade (1985), Boersma (1989), Nieuwkamer (1995) and De Kok and Wind (2002)) is followed for the design of the DSS. The steps that are commonly found in such a strategy are:

1. Describing the problem, including objectives, values and criteria, and boundaries and constraints.
2. Identifying, designing, and screening alternative management measures.
3. Analyzing the impacts of these measures on the achievement of objectives.
4. Comparing and ranking the alternative measures according to the criteria.

These steps can be translated to the specific situation of DSS development. A diversion is made between the first step (model coupling) and the other three steps (model selection). Model coupling can be described as:

1. Selecting the relevant processes and variables using the management objectives and measures as a starting point, developing a qualitative network of interactions (system diagram) and describing values and criteria.

Model selection can be done by:

2. Identifying, screening and, if necessary, designing of alternative models.
3. Analyzing the quality of these models in functioning as a part of the system diagram.
4. Comparing and ranking the alternative models according to the criteria.

A graphical representation of the approach is given in figure A-1.

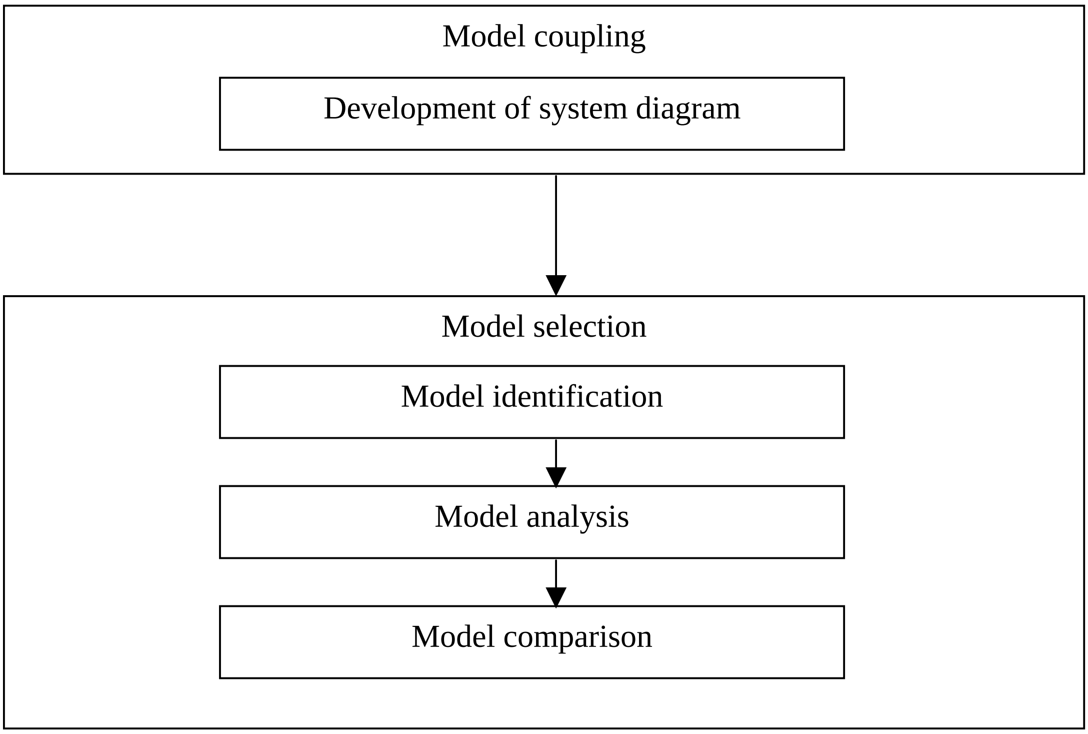

Figure A-1: Top-down approach

Appendix B: Bottom-up approach

When using the bottom-up approach, one starts with the existing research (in this case the available models) and the development of the end-product is based mostly upon the existing form and function of this research (McIntosh et al., 2000). So the existing models form the base and the specification of the system skeleton of the DSS is done after it is observed how the models can be coupled with each other. Successful examples of bottom-up approaches can be found in the literature (Georgakakos and Yao (2000), McIntosh et al. (2000) and Great Lakes Commission (2002)), although it is suggested in the same literature that in the future, projects should first define their purpose then select, evaluate and adapt sub-models in a top-down, purpose–driven rather than model-driven manner.

When one uses a bottom-up approach, model coupling will be done after the model selection (see figure B-1). Because no system description is available, model selection has to be done in the following way:

1. Identifying, screening and, if necessary, designing of alternative models.
2. Analyzing the quality of these models based on internal consistency.
3. Comparing and ranking the alternative models according to predifined criteria.

Model coupling, in this case, can be defined as follows (McIntosh et al., 2000):

4. The evaluation procedure, that determines how well each selected model meets the information demands of other models and of the whole system.

This approach is more ad-hoc than the top-down approach and that is why this approach may not always be successful or efficient. The major requirements for the use of a bottom-up approach are (McIntosh et al., 2000):

1. Having a loosely defined purpose for the whole system (e.g. no specified measures and a lack of specific end-users) resulting in few global information requirements and a greater flexibility in integrating the available models.
2. Complementary of the available research resulting in functional complementary between candidate sub-models.
3. Permitting straight integration, integration after adaptation or integration after a complete rebuild.

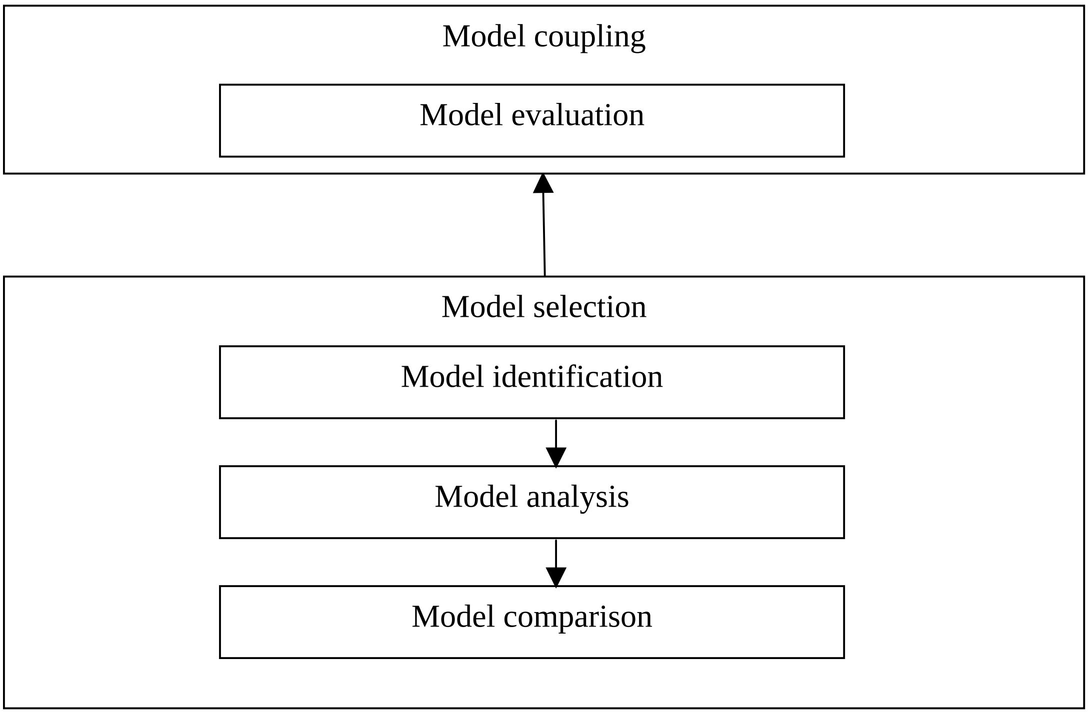

Figure B-1: Bottom-up approach

Appendix C: Selection processes at other projects

WadBOS

A DSS project, that has a lot in common with the nofdp project (e.g. ecology was incorporated to a certain extent), is the WadBOS-project (Engelen, 2000). This project is aimed at constructing a DSS to streamline the process of developing policies relative to the exploitation or protection of the Dutch Wadden Sea. The actual version of this DSS features an integrated model representing the ecological and the economic functions of the sea at three different spatial scales.

The design of the model base was done with a top-down approach and the developers of the DSS used two techniques to do this: Knowledge Engineering and Systems Analysis (Engelen, 2000). Knowledge Engineering (see for example Studer et al., 2000) and Systems Analysis (see for example Schwetman, 1998) are not entirely different, but differ in that Knowledge Engineering is more purpose driven than Systems Analysis and that Knowledge Engineering gathers primarily information from experts. In fact, often they can be complementary to each other, because they both have a top-down view. The major characteristics of Systems Analysis are, that it is more research driven than Knowledge Engineering and that it gathers primarily information form literature research and the analysis of policy documents. One may suggest that the fact that it is research driven, proves that this is a bottom-up approach, but in fact it is just a technique of resembling the necessary information. The end purpose of the DSS is always kept in mind and forms the basis of the research.

The developers of WadBOS organised three knowledge-acquisition sessions and the results of these sessions were coupled back to the Systems Analysis each time so that an optimal synergy between these two techniques would take place (figure C-1). During the first session round, interviews were held with an extensive group of potential end-users, to get an idea of the necessary issues of concern, potential policy levers and indicators and the optimal spatial and temporal resolution. With these results, literature research and an analysis of policy documents was carried out, so that submodel slots could be identified and an initial system skeleton specification could be obtained.

During the second round, the developers set up structured interviews with a large group of domain experts. The results of these interviews were fed back to the experts and discussed until there was a consensus about the fact that all information constraints were met in a right way. The qualitative models that resulted from these discussions were translated into mathematical representations, until all sub-models were fully designed. To the extent possible, existing models were selected, incorporated, adapted or rebuilt for this purpose.

In the third knowledge-acquisition round, the end-users, domain experts, scientists and model developers were confronted with the resulting mathematical representation of the system. These mathematical models were improved during this session and afterwards the implementation of the models and the system as a whole could start.

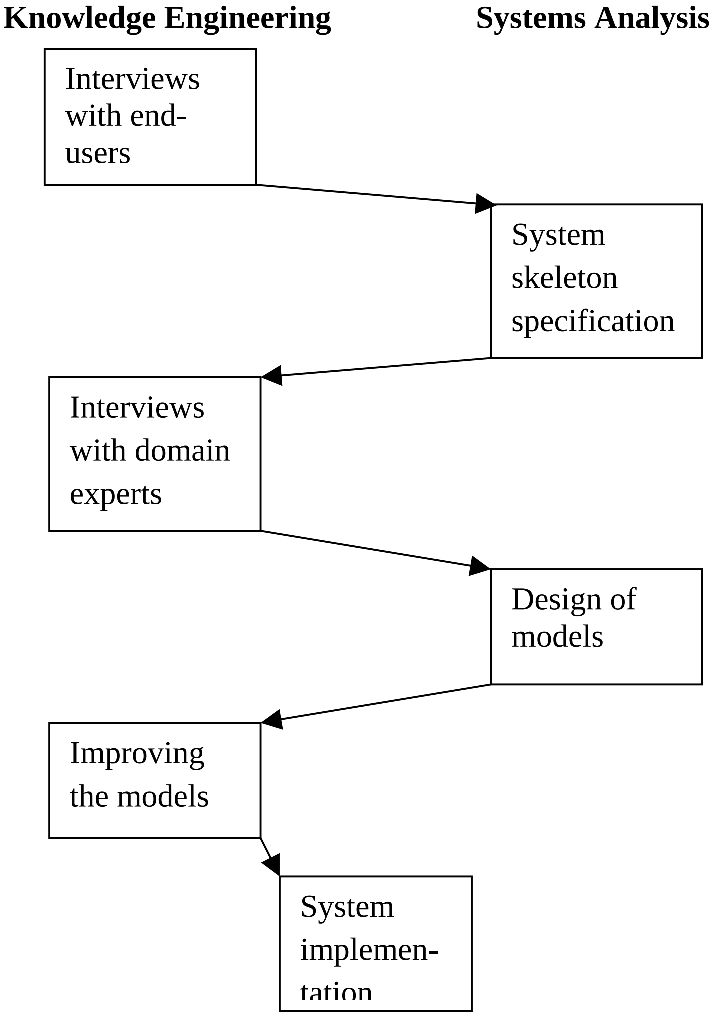

Figure C-1: Modelling process flowchart for the WadBOS DSS

For the selection of the models, end-use and scientific criteria were formulated (table C-1). Although these criteria were rather well-defined, often choices had to be made between accuracy and simplicity. This is because the 'best' model is the simplest one needed to rank the management alternatives according to the objectives of the end-users. By balancing the power of a model to distinguish alternative measures and its complexity it should be possible to identify the appropriate model (De Kok and Wind, 2003 and De Kok and Holzhauer, 2004).

Table C-1: Criteria for model selection at the WadBOS project

Category	**Criteria**
End-use criteria	All processes
	Spatial scale
	Time horizon
	Routine data
	Output centred
	Policy centred
	Interactive
Scientific criteria	Models fitting in the integration scheme
	Time scales and temporal dynamics
	Spatial resolution and spatial dynamics
	Compatibility of scientific paradigms
	Scientifically proven

Because WadBOS used a clear top-down approach for the design of the DSS, a clear system diagram was available after discussion with experts, and model coupling could almost totally be done by means of this system diagram. This diagram is presented in figure C-2 where the boxes represent sub-models and the arrows between the boxes show the main data flows in the model. It is also possible that the sub-models consist of other sub-sub-models.

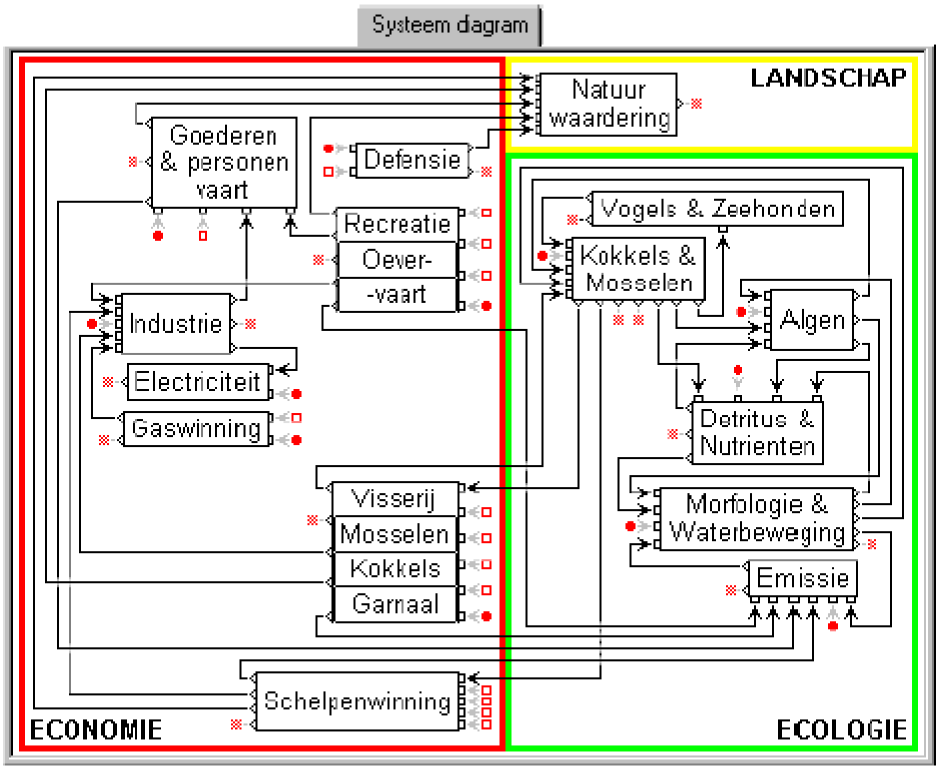

Figure C-2: System diagram of the WadBOS DSS (Engelen, 2000)

When selected sub-models were not able to be put straightforward into this system diagram, three solutions were possible:

1. Existing models were adapted if only minor repairs or reformulations of the model, its algorithms or code were required to have it perform its tasks more appropriately;
2. Rebuilding was necessary when an existing model needed major repairs and adaptation in order for it to fit in the integration scheme;
3. Development of new models is considered when there are progresses in the integration scheme for which models are missing.

It was possible to apply sub-models running at different spatial and temporal scales, because the DSS used three different spatial scales:

1. the Wadden Sea as a whole
2. 12 compartments of the sea
3. a cellular representation of the sea: 11.000 cells of 25 ha. each

and three temporal scales:

1. one tidal cycle
2. one month
3. one year

The DSS typically performs a run of 10 years and shows its outputs every month. The tidal cycle outputs are integrated over the month. A model run takes less than 10 minutes on a state-of-the-art PC. Sufficient GIS data are available at a 500 m grid resolution and statistical data for the economic and ecological models are also available.

The scaling problems faced, when coupling the three levels, were decreased by using a single systems model with access to original models. With this approach to model integration, the architecture represents the watershed by means of an integrated model, but one that permits access to more precise, original models for a selected set of processes (Hahn and Engelen, 2000). So, the output of the models on the detailed level can be exchanged with those in the higher levels and visa versa.

Elbe-DSS

The main target of the development of the DSS for the Elbe-river (Matthies et al., 2003) is to support decision makers in answering important questions in relationship with river basin management and to create a model base that contains some qualitative links between the different factors, that influence the river basin. The DSS contains four different levels: catchment area, flow network, major stream and river track. In the future, scenario analyses for different aspects will be possible and the possibilities of transferring the DSS to other river basins are studied.

Also in this case, the design of the DSS was done with a top-down approach, but the sequence of activities differed from the WadBOS project. At first, user demands were specified. An analysis of the potential users and their wishes regarding the DSS formed the basis for this specification. With this analysis, performance criteria were formulated that contained possible scenarios, issues of concern, policy levers and policy indicators.

After the specification of the user demands, a system diagram was developed and improved. First, a general system diagram was constructed, that contained some basic elements. After that, the basic elements were specified and for all elements, parameters were identified, that described them in an appropriate way. The development of the system diagram ended with the coupling of the elements and parameters.

After the system diagram was built up, the optimal spatial and temporal scales for the different levels were determined. This theme was already discussed during the early stages of the development, but further improvements were made after the user recommendations were given and the important issues and the policy levers were identified. For the river basin for example, the spatial scale was a sub-catchment and the temporal scale was in the order of many years; for the river track, the spatial scale was 10 m and a very fine temporal scale was used.

This information formed the basis of the model selection process. It was demanded that only models, that were developed for the research group “Elbe-Ökologie” and the project “Elbe 2000”, could be incorporated. Except of these models, also an external hydraulical model was evaluated. For the selection of the evaluated models, the criteria in table C-2 were developed and used.

Table C-2: Criteria for model selection at the Elbe-DSS project

Category	**Criteria**
User criteria	Models applicable for the investigation area
	Practical formulation of measures and development goals
	Transparency
	User friendly model management
	Interactive model
Technical criteria	Length of model run
	Model size
	Source code (language, platform, compiler)
	Need for special extern solver-software
	For simulation models: is intervention in the simulation possible?
	Software-architecture
	Does the model need large data sets?
	Flexibility: ease of adaptation and development
Scientific criteria	Input-output criteria
	Fit in the system diagram
	Quantitative system consistence
	Spatial scale
	Temporal scale
	Time horizon
	Compatibility of scientific paradigms
	Scientifically accepted (published) or new?
Organisational criteria	Ownership of the model
	Availability for the Elbe-project, open source code
	Documentation

For all models, model description forms were developed, that contained the main characteristics of the model, the model structure, the input needed, the output generated and the availability for the DSS. These model description forms were compared with the criteria in table C-2 and for the four different levels, the most suitable models were chosen and coupled with each other.

Just like the WadBOS DSS, the Elbe-DSS also uses (four) different spatial scale levels (modules) to incorporate sub-models with different spatial and temporal scales. Different system diagrams for each module are designed and it was observed which of the selected models could be used to model the different processes. Only existing models were built into the DSS, so no development of new models took place.

The four modules are, in turn, linked together in a top-down way, by selecting output variables of the higher-level modules that form input variables for the lower-level modules. This top-down integration could have consequences for the type of models needed. The incorporation of water quality in the river network module, for example, requires a pathway model for pollutant transport in the catchment module.

Also the Elbe-DSS faced problems related to the various spatial and temporal scales of sub-models. An integrated DSS architecture has to deal with these scales simultaneously and in an integrated way. To handle multiple spatial scales in integral dynamic models, the Layered Cellular Automata (LCA) technique was proposed. Discrete event simulation controller in turn was presented as a possible solution for the temporal scaling problem. For details about these techniques, see Hahn et al. (2000).

MODULUS

The main objective of the MODULUS project (McIntosh et al., 2000) was to produce a spatially explicit, generic DSS for application to integrated environmental policy making at the regional level. Therefore, only one spatial scale was used (resolution of 1 ha). To accomplish this, the project set out to review, select, evaluate and potentially adapt existing models from an identified group of EU-funded research projects. These models were taken as a basis for the further design of the project and that is why the design approach can be seen as bottom-up.

Although no definitive model purpose statement, except of the vague description in the first sentence, was produced for the MODULUS DSS, several aspects of the system were tried to examine. These aspects contained the end-users, the issues of concern, the policy levers, the policy indicators and the temporal and spatial scale. Together these features defined the basic structure for the MODULUS DSS and guided the model selection.

To facilitate model comparison and selection, a set of model description characteristics was agreed upon early in the project and the obtained model description forms were used to provide the information required for model selection. Finally, models were selected through an informal process from a limited set of available models from the group of EU-funded research projects by comparing the model description forms with agreed end-user, scientific and technical criteria (table C-3).

Table C-3: Criteria for model selection at the MODULUS project

Category	**Criteria**
End-user criteria	Processes
	Scientifically proven
	Spatial issues (focus on desired output)
	Temporal issues (focus on desired output)
	Routine data
	Output centred
	Interactive
Scientific criteria	Temporal issues (focus on domain processes)
	Spatial issues (focus on domain processes)
	Compatibility of paradigms
	Sub-model functionality
	Level of sophistication
Technical criteria	Software component development

The results of the sub-model selection process are summarised in table C-4.

Table C-4: MODULUS sub-model selection results (McIntosh et al., 2000)

Sub-model slot	**Model selected**	**Contributing project/partner**
Pumping	Pumping model	Archaeomedes
Weather	PATTERN Weather and Storms	EFEDA
Hydrology and slopes	PATTERN Hydrology	EFEDA
Crop Growth	PATTERN Plant Growth	EFEDA
Natural vegetation	RBCLM2	ModMED
Aquifer	Aquifer Model USGS MODFLOW	Archeomedes/IERC Archeomedes/AUA
Catchment	Catchment Model	ERMES
Crop type decision	Decision Making Model	Archeomedes
Land-use	Constrained Cellular Automata Model	RIKS bv.

The MODULUS project, only using existing sub-models, lacked a system diagram at the stage that model coupling took place. But to evaluate the functionality of the sub-models selected for MODULUS, the ‘ease to fit’ for each sub-model was defined. By making an IFT, the set of demand input variables of the sub-models was compared with the set of generated output variables of other sub-models. With the obtained IFT, it could be seen how well the local and global information requirements would be met with the selected sub-models. The IFT was compared with a list of required input for each sub-model so that the functionality of the sub-models could be assessed.

Great Lakes / St. Lawrence system DSS

After three European DSS, where the selection processes had a lot in common, an example of the development of a DSS in the United States and Canada will be discussed. Through the development of a water resources DSS for the Great Lakes and the St. Lawrence river basin (Great Lakes Commission, 2002), the Great Lakes Commission is developing the framework for a DSS that has to provide data, information and processes to ensure adequate public policy decisions concerning the use and management of ground and surface water. Just one spatial level is observed: the Great Lakes and their catchment areas.

It is stated by the commission that users of the DSS have to select the models themselves, so that they only made an inventory of the models to support the model selection process that has to be carried out by the model user. When the model inventory took place, only the main purpose of the DSS and some policy indicators were clear and although it was clear which five categories of models would be reviewed, no real identification of issues of concern, policy levers and sub-model slots had taken place, what made the design of the DSS bottom-up. The identification of relevant models was based on a literature and web-based search, as well as on professional judgement.

When models addressed more than one issue, they were evaluated for more than one category. This evaluation took place by means of information related to key features (table C-5). After the inventory, some guidelines were developed which could be helpful for the selection of models from the inventory. These are also shown in table C-5. Finally, the commission states that model users should carefully define the management problems, and gain a full understanding of the system before selecting models. Applying them on a site-specific basis may require specific knowledge. Resource and data availability for a given site are critical considerations in the model selection process.

Table C-5: Key features for model inventory and criteria for model selection

Key features for inventory	Primary purpose of the model
	Past applications and experience
	Applicability to assess policy indicators
	Ease of use
	Strengths and weaknesses
	Information on how to obtain the model
Criteria for selection	Management objective
	Global modelling objective
	Spatial and temporal scales
	Constituents of concern/stressors
	Resources available
	Constraints
	Level of analysis

With other words, besides these criteria, also local circumstances such as the type of the water body, important processes for water quality etc. can play a key role in the selection. But because it is case specific to what extent such factors are important, these are not added to table C-5.

Just as the MODULUS project, the Great Lakes/St. Lawrence project also had no system diagram at the moment of model selecting and coupling. Just a probable way in which selected models could be coupled was suggested. Figure C-3 illustrates the five categories of models and their potential interconnectivity. The output of a category can serve as input for another.

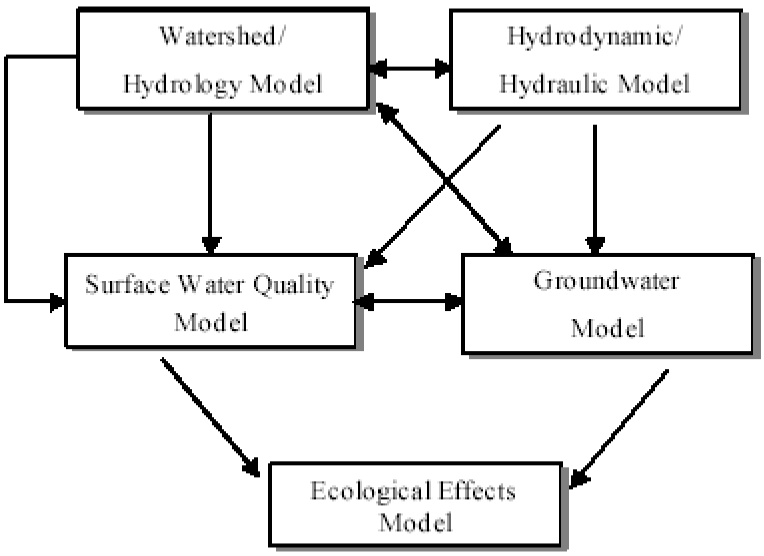

Figure C-3: Interconnectivity of the model categories for the Great Lakes /St. Lawrence DSS (Great Lakes Commission, 2002)

Dommel DSS

The aim of the EU-LIFE Dommel project was to develop a method for the combined use of landscape ecological models and socio-economic knowledge in the development of integrated management plans for catchment areas of small trans-border rivers (Verkroost et al, 1998). These methods were developed and tested in the catchment area of the river Dommel.

This project used a top-down approach, so first, a preliminary study was carried out to get a clear insight in the major environmental problems, their relations to human impacts and bottlenecks for attaining a higher ecological quality. Relations between socio-economic developments and their impacts on nature were analysed. Furthermore, an analysis was made of the goals, organisation and instruments of policy. After this preliminary study, priorities were established concerning the environmental impacts and ecological responses, which should be included in this prediction model. These priorities were based on the preliminary study, policy preferences and technical possibilities of model construction.

Related to these priorities a number of hydrological and ecological models were developed, which were linked with one another and with a GIS, based on literature and expert knowledge (figure C-4). The DSS is used to predict the effects of different land use and water management scenarios on the selected ecosystems. So the ecological models (ALNION, MOVE and ECOSTREAM) are the heart of the integrated model. The other models (MODFLOW, SMART and STREAMFLOW), connected to land use and water management, were developed in such a way that they provided the necessary input parameters for the ecological response models.

In this project a coupling is made between existing models and newly developed models. The models MOVE (for grasslands), MODFLOW (groundwater) and SMART (soil moisture quality), with which there is a lot of experience, were coupled with ALNION (for woodlands), ECOSTREAM (for aquatic ecosystems) and STREAMFLOW (rainfall-runoff, hydraulics and surface water quality), models that were specially built for this project.

The structure of the DSS and the information flow has a lot of similarities with that of the Great Lakes/St. Lawrence System DSS. The major differences of the structure are that in the Great Lakes/St. Lawrence DSS, just one ecological model was used and that hydrological, hydraulical and water quality models were separated. Major differences in the information flow are that in the Dommel DSS, the hydrological/hydraulical model was directly coupled with an ecological model and that the water quality has no influence on the groundwater.

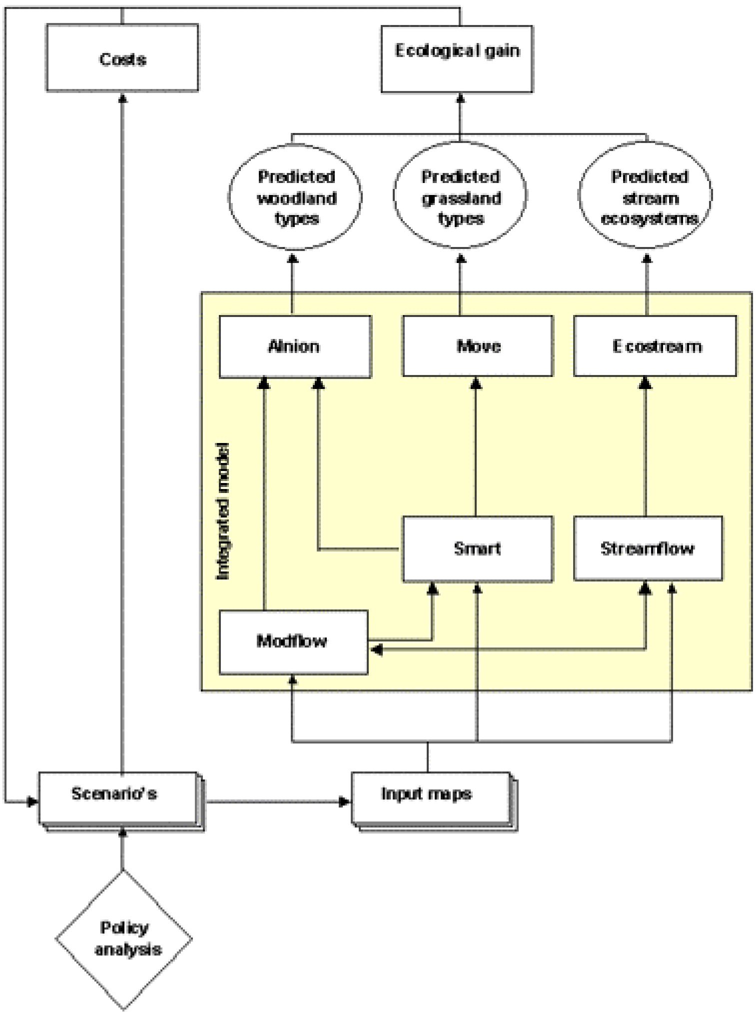

Figure C-4: Way of coupling models for the Dommel DSS (Verkroost et al., 1998)

Appendix D: Component Based Development

From working group meetings in Vught and Darmstadt, it became clear that the IDSS should have certain generality and flexibility and that existing models should be re-used as much as possible. It was also suggested that users should be able to plug in their own models. In this section, it will be explained how state of the art software technologies enable to develop information systems that use and integrate existing parts to a large extent. The integration effort does not stop with the delivery of the first prototype but is a constant activity during the whole lifecycle of the system. The most often used state-of-the-art software engineering method to achieve these goals is *Component Based Development* (CBD).

The basic idea of CBD is old, simple and powerful: to build a complex whole, try to assemble it from less complex parts, which the DSS developer might already have (Hahn and Engelen, 2000). Within a CBD framework, software parts are designed according to predefined specifications, so they can be assembled together to create entire applications. These parts are known as *components*. Because CBD systems are built using components that all conform to predefined specifications, changes and enhancements can happen more seamlessly. The need to build new components or the system to which they are being added is minimised (McInnis, 2002).

A software component is made up of three essential parts (McInnis, 2002):

1. The *interface*: An interface tells the user of a component or other components what the component will do. Users or components would not know how to use a component if no interfaces were provided.
2. *Implementations*: An implementation is the code that makes the component work. A component may be built with more than one implementation.
3. The *deployment*: The deployment of the component is the physical executable file that is used to make the component run.

In addition to these three necessary parts, a component must possess certain properties (McInnis, 2002):

- A component is *encapsulated*. This is the process of hiding the implementation or code that drives a component. The major advantage of encapsulation lies in a component's ability to accommodate changes in its implementation without affecting consumers of the application since the interface remains undisturbed by developers.

- A component is *descriptive*. Since a component is encapsulated, which means it can only be accessed through defined interfaces, it must furnish information about itself that allows consumers to understand it.
- A component is *replaceable*. These properties make it possible to replace one component with another as long as it offers the same set of interfaces.
- A component is *extensible*. The extensible property of a component means that it is possible to extend its range of services without affecting consumers.

There are some major advantages of building software systems from components, including reduced costs, higher productivity and more *flexibility*:

- The most significant way in which creating software applications with components can serve to reduce development costs is through reuse. Since software components are built to well-defined specifications, their capabilities are easier to ascertain. When it is easier to understand precisely what a component will do, it is also much easier to assess whether the services it offers can be used to build another application or system. In addition to reducing costs, reusing existing components increases productivity since application development teams don't have to begin building new applications from scratch.
- Building with components also reduces maintenance costs. Since components are encapsulated, it is possible to make changes to their implementation without affecting all the systems that rely on them.
- Finally, component technology also can help to increase the flexibility of the DSS by decoupling its components (e.g. tools, models, GIS access and user interface) and introducing interfaces as their only way to exchange information among each other. For example separating the user interface layer from the *model engine* yields a much more flexible architecture. A stand-alone version and, for example, an internet version of the IDSS could then be built with identical model engines but different front-ends. The model engine would not even need to know to which kind of front-end it is connected. Of course, the same holds for the various tools needed in the IDSS. By ensuring that all information exchange between the tool and its environment goes via its component interface, the internal structure of the tool is completely hidden (Hahn and Engelen, 2000).

Application frameworks are built upon CBD and go even further in achieving *reusability*. They are generally open systems that leave the end-user some choice which models to use. The objective of a framework is to provide a mechanism by which existing models can be linked or organised in a consistent manner. This makes an application framework *generic* and flexible and so very suitable for coupling existing models and giving freedom to users to use their own models.

Several initiatives have delivered or are developing modelling frameworks with this aim, but, in general, little is documented about them. An exception is Geonamica, with which DSS as WadBOS, MODULUS and the Elbe-DSS were built. During the study, two examples of application frameworks that will be finished in the next year (2005) and that seem very interesting for the coupling of the models were investigated: the *Generic Framework Water* (GF, see section 4.4.1) and the HarmonIT project or *Open Modelling Interface* (OpenMI, see section 4.4.2).

Appendix E: Questionnaire for the water board interviews

General questions:

1. Is model application customary in your water board?
2. Which models are in use at the water board for realizing former as well as current or future investment projects?
3. Which issues are mainly addressed in these models (e.g. ground water, water flow, rainfall-runoff, water quality, sediment transport, morphology, salt intrusion, ecology)?
4. At which stage of the planning process are the models involved?
5. Are the models run internally or by external consultants?

For each model

User questions:

1. Which processes are employed by the model?
2. As what type of model can it be classified (e.g. empirical, dynamic, stochastic, deterministic)?
3. Are the essential input data for the model available at the water board or is extra-survey necessary?
4. How is the user interface set-up?
5. Is the model set up of components?
6. Do the components run individually?
7. How do the components communicate?
8. Is the model coupled with GIS-tools?
9. How are specific measures of the investments implemented into the model?
10. Is user interaction demanded or optional during a run?
11. Are the model-run and the model-output understandable and well documented?
12. What tools are available in the system to support the user in carrying out the analytical tasks without having to fall back on other software or analytical instruments?
13. Does the model have any optimization techniques?
14. Do the model and its results give helpful support to the user in taking decisions on the planning of the investment?

Scientific questions:

1. Is the model built by own experts or set up externally?

2. What temporal scale is used?
3. What time horizon can be observed?
4. What spatial scale is used?
5. What kind of input is required to run the model?
6. What kind of output is generated by the model?
7. Which assumptions and hypotheses are built into the model?
8. For ecological models: What indicators are used for describing the ecological conditions?
9. For ecological models: what are the most relevant parameters describing the biological habitat?
10. Is the model only applicable to the target area of investment or can it be transferred to other areas?
11. How is the Model calibrated or validated?
12. How big is the flaw of the model?

Technical questions:

1. Is the model composed of relatively independent modules?
2. Can component pieces easily be extracted?
3. Can it be adapted or developed easily?
4. In which implementation language can it be adapted or developed?
5. Are there any interfaces to other models?
6. Which import and export data is the model able to handle?
7. How long does a model run take?
8. Is the model spatial or non-spatial?

8a. When no, can it be easily spatialised?

8b. When yes, how is it spatialised?

9. What is the implementation language of the software code?
10. Does the model need any special extern solver-software?
11. Does the model need large data sets (depending on the application area)?
12. Is the data saved in a relational data base or in ASCII files?

Organizational questions:

1. What is the development status of the model? Is it already implemented or still at a conceptual phase?
2. When it is already implemented, is it been scientifically accepted (published)?
3. Is there any documentation about the model?
4. Is the software free or commercial?
5. Does the water board have the owner rights of the model?
6. Was a cost-benefit analysis carried out for model application?
7. Is there an estimation of costs of model application per investment?
8. Are the essential input data for free or is it necessary to pay for them?

9. Are you satisfied with model application and results in your water board referring to the investments?
10. Do you see any deficits and related to that: do you see any vital future developments?
11. Do you feel your models would be helpful for the nofdp-project, esp. for building the IDSS-software?

Appendix F: Interviewed persons

Tim Raats	Water board Aa en Maas	8/20/2004
Dolf van de Voort	Water board Brabantse Delta	8/20/2004
Aart van Wessel	Water board De Dommel	8/25/2004
Drs. Perry de Louw	TNO-NITG	8/30/2004
Heinrich Hess	Water board Mümling	9/22/2004
Matthias Sottong	Water board Mümling	9/22/2004
Christian Fritsch	Brandt · Gerdes · Sitzmann Wasserwirtschaft	10/13/2004
Dr. Stefan Wallisch	Brandt · Gerdes · Sitzmann Wasserwirtschaft	10/13/2004

Appendix G: Model description forms

DIWA

Used at Brabantse Delta

1. Addressed issues

Surface water quantity.

2. Internal/External

The model is run internal. The water board has the owner rights of the model.

3. Development status

The model is used a lot in the past to model reparcelations. In 1998 it has been integrated into SOBEK. Nowadays, it has been replaced by DUFLOW. It has been published for the dimensioning of water streams. There is documentation about the model.

4. Costs

DIWA is free, it is used rarely. The water board has the necessary input data.

Strengths

For free

Weaknesses

Rarely used

DUFLOW-water quality
Used at Brabantse Delta

1. Addressed issues
Water quality
2. Processes modelled
Transportation of substances in free surface flow
First order advection
Diffusion
Oxygen transport
Mud transport
Eutrophic processes
Water temperature
Variable dispersion
Transfer of substances at artificial objects
The user can define other processes.
3. Class of models
Dynamic, fysical-deterministic
4. Model input
Discharges (m^3/s)
Velocities (m/s)
Water depths (m)
Initial concentration (Ammonium, nitrate and phosphor) (mg/l) or
Initial load (Ammonium, nitrate and phosphor) (g/s)
Process description
Optional:
Algae type
Higher trofic levels
Water plants
C/N C/P relation (constant or variable)
Day mean light limitation
Temperature algae grow
The data format is ASCII.
5. Outputs generated
Nutrient concentrations (mg/l)
Nutrient loads (g/s)
Files are saved both in binary .bmf and ASCII .xml files.
6. User possibilities
Because the module has an open set up, users can define their own water quality processes. Also, some standard processes are included in the package. In DUFLOW-water quality, a distinction is made between substances which are transported with

the flow of the water, for instance dissolved substances, and bottom materials that are not transported. This distinction offers the user the facility to, for instance, study the interaction between the bottom materials and the dissolved substances in the water above. Finally, the aquatic ecosystem model PCLake can be coupled with DUFLOW, so that the effects of water quality on ecosystems in lakes can be calculated. Limited user support is available. Computation time is usually in the range of minutes up to one hour.

7. Modularity

The water quality module is a part of the total DUFLOW model, but is easy to extract. The module is linked with the water quantity module. It is, however, impossible to link the module with SOBEK-CF.

8. Temporal scale

Δt = 30 s, 1 m, 5 m, 10 m, 30 m, 1 h, 3 h, 6 h, 12 h, 1 d or 12 d

T = 1 s – many years

9. Spatial scale

Non-spatial module, not scale-bounded processing of concentrations.

10. Uncertainty

The assumptions that are underlying the model are (Stowa / MX.Systems, 2002):

The one dimensional transport equation is valid at all times and all places.

All water in a cross section is the same, there are no gradients from bottom to top.

The density is assumed to be constant.

The biggest limitations of the model are:

The model is not suitable for flows in which an extra spatial dimension is of interest. Water bodies with significantly different velocities in the vertical, such as stratified waters, can therefore not be modelled.

The numerical solution method does not support supercritical flow.

11. Level of genericity

Except for water bodies with significantly different velocities in the vertical and supercritical flows, the model is suited for all types of water bodies. Because it is a far field model, it is also not suited for the estimation of local effects.

12. Internal/External

Duflow is developed by IHE, the Dutch Ministry of Public Works, the Technical University of Delft, Stowa and Wageningen University and Research Centre. The model is run internally at water board Brabantse Delta and the water board has the owner rights of the model.

13. Development status

In 1992, version 2.0 of DUFLOW was developed that included a water quality module (Stowa / MX.Systems, 2002). Afterwards, the module has been updated several times. The water quality module can be calibrated by adjusting parameters that control the dispersion or parameters that are known to influence the water quality process in an important way to a reasonable level, while approaching known results for concentrations of a certain substance. Validation can take place afterwards by running the calibrated model with independent data (ideally several independent data sets) without changing the calibrated parameters. In the past, a lot of experience is obtained with agricultural consolidation. The DUFLOW model is not used so much, but for water quality problems, this module is used in general. It is scientifically accepted and a user's guide is available. Future developments are mainly in the improvement of the user friendliness, like the coupling with GIS-tools.

14. Software code

The computational core of this model is based on the FORTRAN computer code IMPLIC which is originally developed by Rijkswaterstaat (Stowa / MX.Systems, 2002).

15. Costs

STOWA-members: Purchase for free, user support and updates: € 795/year.
Other organisations: Purchase: € 2090, user support and updates: € 995/year.
Prices are for both DUFLOW quantity and quality
(see www.mx-groep.nl/producten/Duflow/Duflow-web/pages/prijzen.html).
The water board has the necessary data.

16. Satisfaction

Although, the module is not suitable for stratified waters, supercritical flow and local scale problems, it is useful for problems on a larger spatial scale. There are good experiences with the modelling of water quality for investment projects. The water board thinks it can be of use for the IDSS.

Strengths

Suited for observing complete flow networks
Possible to introduce new processes into the model
Easy to extract the module
Often used in the past
Users can observe many different time horizons and make the calculations with many different time steps.
Simple schematisations can be made in little time.
Only model that can fulfil the need for a water quality model

Weaknesses

Not suited for water bodies with significantly different velocities in the vertical
Not suited for supercritical flow
Not suited for estimating local effects
Not for free
Impossible to couple with SOBEK-CF.

DUFLOW-water quantity
Used at Brabantse Delta

1. Addressed issues
1-D water movement
2. Processes modelled
Non-steady flows
3. Class of models
Dynamic, physical-deterministic
4. Model input
With some help of the network-editor in the user interface, it is possible to put up the schematisation of the network of water streams. On each stream in the network, measures can be defined. The data format is ASCII.
Compulsory parameters:
Theta
Network
Boundary conditions:
- Water level (m) or
- Discharges (m^3/s) or
- Q-h relation

Wind direction
Wind velocity (m/s)
Structure shape
Cross sections:
- Length (m)
- Bed level (m)
- Roughness of the bed (Chezy-value), can be defined as a constant, but also as a function of the water level
- Wind conversion factor
- Shape of the cross section
- Streaming width and conservation width
- Streaming surface
- Hydraulic radius

Weirs:
- Crown width (m)
- Crown height (m)
- Mu overflow

5. **Outputs generated**
Outputs:
Discharges (m^3/s)
Water levels (m)

Velocities (m/s)
Water depths (m)
ASCII files are generated according to the standardised language XML. This format can be read in by many standard libraries.

6. User possibilities

The user interface of DUFLOW consists of a menu-bar, a standard task bar, a Network-editor (network can easily be built), Scenario-Manager (computing scenario's and comparing the results of the different measures with each other) and an extensive presentation module. Limited user support is available. Computation time is usually in the range of minutes up to one hour. A user's guide is available.

7. Modularity

DUFLOW consists of 4 larger, independent modules, which can be extracted easily:

1) DUFLOW Flow and Quality including the possibility to incorporate user-defined equations;
2) RAM, the precipitation run-off module;
3) MoDuflow, the coupling between MODFLOW and DUFLOW, describes both ground and surface water flow. With MoDuflow the interaction and total water balance of ground and surface water is solved more realistic than when a static modelling in MODFLOW en DUFLOW has to be made;
4) TEWOR can be used to evaluate the effect of sewer overflow situations on the water quality of the surface water.

The water quantity module can easily communicate with the other modules and can run in combination with them. It can also run individually. DUFLOW can import IMWA-files and can read shape-files and Autocad-files (*.dgn, *.dwg, *.dxf) as geographical background. Engineering company Tauw has made a coupling between DUFLOW and ARC/INFO. Also an interface is made with the groundwater model Triwaco (Royal Haskoning) and with the module MoDuflow an on-line coupling is made between DUFLOW and the groundwater model MODFLOW. Consultancy company Hydrologic has made some useful couplings to convert DUFLOW-quantity schematisations into SOBEK-CF schematisations. Finally, the aquatic ecosystem model PCLake can be coupled with DUFLOW, so that the effects of water quality and quantity on ecosystems in lakes can be calculated.

8. Temporal scale

Δt = 1 year, day, hour or minute
T = dependent of input

9. Spatial scale

Non spatial module

10. Uncertainty

The assumptions made in the model are the following (Stowa / MX.Systems, 2002a):

- DUFLOW assumes the laws of conservation of mass and impulse. These laws are translated to mathematical equations.

- DUFLOW calculates water movements in 1 dimension. This is why density flows and flows in turns cannot be calculated.
- DUFLOW pronounces the theoretical water levels and flows very accurate. For water quantity, reliable results can be obtained. For water quality also, but only when the whole calculation runs stable.

11. Level of genericity

The model is generic.

12. Internal/External

DUFLOW is developed by IHE, the Dutch Ministry of Public Works, the Technical University of Delft, Stowa and Wageningen University and Research Centre. The model is run internally at water board Brabantse Delta and the water board has the owner rights of the model.

13. Development status

In 1988, DUFLOW 1.0 was developed by IHE, the Technical University of Delft and the Dutch Ministry of Public Works (Stowa / MX.Systems, 2002a). In 1992 version 2.0 was built together with the Stowa and the Wageningen University and Research Centre. Furthermore, the model was developed after consultation of other engineering groups. A lot of experience is obtained with agricultural consolidation. It is scientifically accepted. In the future DUFLOW will be incorporated into the Generic Framework.

14. Software code

The computational core of this model is based on the FORTRAN computer code IMPLIC which is originally developed by Rijkswaterstaat (Stowa / MX.Systems, 2002).

15. Costs

STOWA-members: Purchase for free, user support and updates: € 795/year.
Other organisations: Purchase: € 2090, user support and updates: € 995/year.
Prices are for both DUFLOW quantity and quality
(see www.mx-groep.nl/producten/Duflow/Duflow-web/pages/prijzen.html).
The water board has the necessary data.

16. Satisfaction

Although, the program cannot handle some of the more-sophisticated modelling needs (e.g., dry beds, automatic gates), it is useful for first-time users of canal-network software. There are good experiences with the modelling of the Mark-river. The water board thinks it can be of use for the IDSS.

Strengths

Dynamic model
Coupling with MODFLOW
Reliable model
Easy to extract modules

Weaknesses

Cannot read all standard GIS-formats

Not for free

Most of the time, SOBEK and SIMGRO are used

DUFLOW-RAM

Used at Brabantse Delta

1. Addressed issues

Rainfall-runoff

2. Processes modelled

precipitation
infiltration to the soil moisture
percolation to the groundwater
groundwater discharge to the surface water
surface runoff
evapotranspiration

3. Class of models

Dynamic, physical-deterministic

4. Model input

Precipitation (mm/day)
Evaporation (mm/day)
Unpaved surface settings:

- I_{max} (mm/d)
- f (-)
- F_0 (mm)
- F_2 (mm)
- $F_{4.2}$ (mm)
- Phi_0 (mm)
- LB_{v0} (mm)
- n (-)
- BL_{min} (mm)
- $P_{percmax}$ (mm/d)
- C_{max} (mm/d)
- $K_{surface}$ (day)
- K_{quick} (day)
- K_{slow} (day)
- B_{slow} (-)

Areas:

- Sub-catchment surface (m^2)
- Land use
- Features of open water
- Features of paved area
- Features of unpaved area

Seepage:

- C (day)
- DH (m)
- Percentage to unpaved

Concentrations ammonium, nitrate and phosphor for all types of areas (mg/l)

The data format is ASCII.

5. Outputs generated

Runoff:

- Open water [m^3/s]
- Paved area [m^3/s]
- Unpaved area [m^3/s]
- Seepage [m^3/s]
- Total [m^3/s]
- Concentration of nutrients in runoff

The data format is ASCII.

6. User possibilities

Limited user support is available. Computation time is usually in the range of minutes up to one hour. DUFLOW can import IMWA-files and can read shape-files and Autocad-files (*.dgn, *.dwg, *.dxf) as geographical background. Engineering company Tauw has made a coupling between DUFLOW and ARC/INFO. DUFLOW can be coupled with the groundwater model MODFLOW. It is the only rainfall-runoff model that can model water quality during the rainfall-runoff process by attaching concentrations to the different partial streams. This has the advantage that it can model diffuse sources.

7. Modularity

DUFLOW-RAM is a module of DUFLOW. The module is built up out of the partial processes infiltration to the soil moisture, percolation to the groundwater and groundwater discharge to the surface water.

8. Temporal issues

Δt = 1 year, day, hour or minute

T = dependent of input

9. Spatial issues

Spatial model

10. Uncertainty

Assumptions (Stowa / MX.Systems, 2002b):

- DUFLOW-RAM assumes the laws of conservation of mass and impulse. These laws are translated to mathematical equations.
- Infiltration capacity is constant in time.
- Infiltration results immediately in percolation.
- In case of water contents larger than those in case of field capacity, the actual evapotranspiration is equal to the potential evapotranspiration.
- In case of saturation, the percolation is equal to the maximum percolation.

- Load is directly proportional to flow.
- No transposition processes in the bottom are modelled.
- DUFLOW pronounces the theoretical water levels and flows very accurate.

11. Level of genericity

The module is generic.

12. Internal/External

DUFLOW is developed by IHE, the Dutch Ministry of Public Works, the Technical University of Delft, STOWA and Wageningen University and Research Centre. The model is run internally at water board Brabantse Delta and the water board has the owner rights of the model.

13. Development status

The Dutch consultancy company Witteveen+Bos developed the RAM module of DUFLOW. Furthermore, the module has been developed after consultation of other engineering groups. A lot of experience is obtained with agricultural consolidation. It is scientifically accepted and a reference manual is available online (www.icimod-gis.net/web/IWRM/module4/module4_4.htm).

14. Software code

The computational core of DUFLOW is based on the FORTRAN computer code IM-PLIC which is originally developed by Rijkswaterstaat (Stowa / MX.Systems, 2002a).

15. Costs

STOWA-members: Purchase for free, user support and updates: € 295/year.
Other organisations: Purchase: € 590, user support and updates: € 295/year.
See www.mx-groep.nl/producten/Duflow/Duflow-web/pages/prijzen.html.
The water board has the necessary data.

16. Satisfaction

There are good experiences with the modelling of the Mark-river. The water board thinks it can be of use for the IDSS.

Strengths

Dynamic model
Can be coupled with MODFLOW
Generates quality of runoff, allowing modelling of diffuse pollutant sources
Reliable model that is often used in the past
Can be extracted easily out of the whole DUFLOW model

Weaknesses

Cannot read all standard GIS-formats
Not for free
Not used so much anymore for water quantity

HYBNAT

Used at engineering company Brandt Gerdes Sitzmann in favour of water board Mümling

1. Addressed issues

Rainfall-runoff-transport

2. Processes modelled

- Runoff development
- Runoff concentration in the partial surfaces
- Transient runoff transport in the water course
- Wave division at branches
- Retention in retention areas

3. Class of models

Empirical (only runoff development and runoff concentration), dynamic, deterministic

4. Model input

Input parameters (see www.bgswasser.de/hybnat.htm):

Precipitation [mm/h or mm/d]

Calibration parameters:

- Discharges [m^3/s]
- Flow volumes [m^3]
- Water levels [m above reference level] (with WASPLA)

Topographic area characteristics:

- Heights [m above reference level]
- Lengths of water courses [m]
- Share of paved area [-]

Soil types

- Land use:
- Share of forest [%]
- Share of agriculture [%]
- Share of pasture [%]
- Share of paved area [%]

Cross sections

The precipitation data are descended from the KOSTRA-atlas or from DWD-stations. Cross section data are available at the water board or at the state of Hessen. All other data are official data that can be obtained for free at for example the State Geometrical Service. Data can be put into the model by implementing them in the different modules with an ASCII editor. The model needs ASCII or ANSI files.

5. Outputs generated

Output parameters:

- Discharges [m^3/s]

- Discharge volumes [m^3]

The model can generate ASCII .dxf files. Data are only saved in ASCII files and not in a data base.

6. User possibilities

HYBNAT has no user interface. User interaction is only necessary when the model indicates that there are unusual aspects. The model run is documented. HYBNAT shows, which data are read in and shows during the simulation, on which point in time the calculation takes place. Results are documented with plots and tables of discharge against time, maximum values for every system element (maximum discharges, maximum volumes and their times of occurrence) and discharges for the total water system for all points in time. Besides that, detail prints can be obtained for every model building block. The program has many help programs and routines such as the help program PROFIL that can make data ready to use. The model has no techniques to choose the best measure. Users say it is only a useful support for planning from a hydraulical point of view and only when it is used in combination with the water surface calculation model WASPLA (Land Hessen, 1996). The model does not need any external solver software. Model runs take a few seconds (5 seconds for models of 3000 elements).

7. Modularity

The model is build up out of twelve relatively independent modules Barben et al., 2001), that are not all necessary to work together. Except of any exceptions, these modules do not communicate with each other. It is easy to extract the modules. HYBNAT is not directly coupled with GIS-tools. It has a data connection with WASPLA.

8. Temporal issues

Minimum time step is one minute, but dependent of the problem it is possible to calculate with larger time steps.

9. Spatial issues

The model uses (sub-)catchments as spatial units, but when necessary, it is possible to use a raster. It can be used for catchments of up to some thousands square kilometres.

10. Uncertainty

Assumptions (Barben et al., 2001):

- All precipitation on paved areas is direct runoff after subtraction of predefined losses.
- Runoff distribution for unpaved areas depends on precipitation height and the CN-value according to the SCS-method or the ZAISS-method.
- Canalised areas use a double retention cascade and ‘natural’ drained areas a triple retention cascade (fourth cascade possible).
- Saint Venant Equations.

The uncertainty in the model system is small.

11. Level of genericity

The use of HYBNAT is confined to secondary mountains and flat areas (Barben et al., 2001). The use of the model for the calculation of extreme floods with exceedance probabilities of smaller then once in 100 years is problematic, because the model cannot be calibrated for those floods.

12. Internal/External

The model is developed and used by engineering company Brandt Gerdes Sitzmann in Darmstadt, Germany. The water board has no owner rights of the model.

13. Development status

The model has to be calibrated manually, without special algorithms or goal functions (Barben et al., 2001). With known precipitation data and runoff data, all other parameters can be calibrated. The model is implemented and published in report nr. 1-19 of the International Commission for the Hydrology of the Rhine basin. Also a short description of the model is available at the water board.

14. Software code

It is easy to adapt or develop the model in Fortran 95.

15. Costs

HYBNAT is given to universities and institutes in individual cases. Brandt Gerdes Sitzmann also offers a project-specific co-operation. All necessary input data are for free.

16. Satisfaction

The water board has positive experiences with the results of the model and think it could be of use for the IDSS.

Strengths

Can model transient flow
Common input data, that are for free
Many help programs and routines
No external solver software needed
Fast calculations
Build up out of components that are easy to extract, adapt and develop
Suitable time step
Possible to spatialise the model
Positive experience at the water board

Weaknesses

Not coupled with GIS-tools
No interfaces with other evaluated models
Unsuitable for mountainous areas
Unsuitable to calculate effects of exceptional precipitation
Has to be calibrated manually
The water board has no owner rights
Commercial product, that is only given to institutes in specific cases

MLAEM (Multi Layer Analytic Element Model)

Used at Aa en Maas

1. Addressed issues

Semi-3D ground water model

2. Processes modelled

2D-groundwater flow inside an aquifer

Areal recharge

Seepage

Infiltration

Withdrawal

Leakage between aquifers

Continues variation of water density

3. Class of models

Dynamic, steady flow, analytical, deterministic, non-linear

4. Model input

Boundaries:

- head at reference point or
- flux or
- linear relation between head and flux

Network:

- base elevation
- hydraulic conductivity
- vertical resistance c* (d)
- drainage resistance c_{drain} (d)
- thickness of the aquifer
- location of leakage points
- water levels in surface waters
- dimensions of water courses
- precipitation residues (m/d)
- initial water density

The model can read ASCII DXF files (Strack and Strack, 1997). The user puts in the data by entering aquifer data and analytic elements into the input window.

5. Outputs generated

MLAEM produces ASCII DXF files that may be read by other programs such as SURFER (Strack and Strack, 1997). Each element is stored with its topographic and geo-hydrologic properties. Data sets consist of small files and are maintained by using a dedicated data management system.

Obtained output:

- potentiometric head
- groundwater levels

- flow velocity and direction
- fluxes
- particle position
- water density
- volumetric budget

6. User possibilities

MLAEM can be accessed by a Graphical User Interface (GUI, see Strack and Strack (1997)). There are three pull-down menus and seven main windows in this user interface that control the operation of the program. The user interface makes it convenient to enter and modify data, usually on a background map. The model run is not transparent, but the output is drawn in well-understandable plots. With available tools, the user can view the parameters of any element in the model, view co-ordinates, generate water particle traces directly and generate ten water particle pathlines that end up at the well. Support is available via e-mail.

7. Modularity

The structure is modular, with a module for each element, and modules for each type of task to build and use the model (Strack and Strack, 1997). These relatively independent modules run individually, but some communicate with each other. Mostly by a module on a higher level of abstraction. Through the command-line interface it is easy to drive the program from GIS-programs such as ArcView and ARC/INFO and the parameter estimator PEST. There are no interfaces with other models, but it should be easy to couple existing MLAEM-models.

8. Temporal scale

The user can define the temporal scale by himself. For groundwater models, a week, a month or a year should be sufficient. Also the time horizon can be chosen by the user.

9. Spatial scale

The model is spatial. It is 2D in-between an aquifer and aquifers can communicate with each other by the leakage points (Strack and Strack, 1997). The number of layers supported by MLAEM is limited only by hardware. MLAEM is not confined to "cells" or "grids" of any kind so there is no real spatial resolution.

10. Uncertainty

The assumptions made in analytic models model are (Haitjema, 1995):

- steady-state flow → retention changes in the groundwater can not be taken along in the calculations
- Dupuit-Forchheimer assumption occurs in each aquifer (vertical resistance to flow is neglected).
- the aquifers are assumed separated by initially impermeable boundaries, they are connected using leakage areas implemented by the user.
- MLAEM assumes the Mass Balance Equation and Darcy’s Law as the basic equations
- aquifers are two- dimensional and isotropic

Because of the continues feature of the model, model output predicts the reality well. On the other hand, because of the many assumptions made, uncertainty increases. Uncertainty analyses by experts show that the uncertainty is considerably larger in areas with a high hydraulic conductivity than in areas with a low hydraulic conductivity. There is also a high uncertainty around the leakage points.

11. Level of genericity

Though MLAEM can be applied to all areas and to all types of soil in the saturated zone, it is less suitable in areas with a high hydraulic conductivity.

12. Internal/External

MLAEM is based on the Analytic Element Method (Haitjema, 1995) developed by Dr. O.D.L. Strack. The computer program was developed by Strack Consulting. MLAEM is run internally at the water board and the water board has the owner rights of the model.

13. Development status

MLAEM has been used in the US, Europe and Africa on numerous projects. Successful applications of MLAEM include the construction of a model of the Toppenish Basin prepared for the Yakima Indian Nation, the groundwater models of Hennepin County by the Hennepin County (Minnesota) Conservation District, the model of Dakota County (Minnesota), the National Groundwater Model (NAGROM) of The Netherlands prepared by RIZA, the Twin Cities Metropolitan Model prepared jointly by the Minnesota Pollution Control Agency and the University of Minnesota, and the regional model of the groundwater system around Yucca Mountain, Nevada, prepared by the University of Minnesota for the USGS. Most of these models are in active use. Because the model is newly used at the water board, there is no experience with using the model for investments projects there. A tutorial is available on the internet (www.ce.umn.edu/~strack/Pdf/manual.pdf). Future developments are a better representation of the influences of the surficial aquifer and functions to represent a continuously sloping aquifer base and leakage between aquifers is simulated automatically and exactly without the need for specifying area-elements for leakage (Bakker et al., 1999). Calibration of a model made with MLAEM can take place by linking measured values of piezometric heads and water balance. Many parameters can be adjusted to fit the model to measured heads. These include hydraulic parameters, boundary head values, and infiltration and leakage values. After values for most of the variables are entered, infiltration and leakage values are generally adjusted to fit the model to the head calibration targets. Infiltration and leakage values can be adjusted using both manual calibration procedures and PEST.

14. Software code

Unknown, but some modules are written in FORTRAN (Strack and Strack, 1997).

15. Costs

The costs of purchasing MLAEM are $5000 (www.scisoftware.com/products/slaem_overview/slaem_overview.html), but for Dutch governmental organisations, it is for free. The water board measures some data, but for soil maps, vegetation maps, geomorphologic maps and precipitation data, a payment has to be made.

16. Satisfaction

Although the water board has no experience with MLAEM, it has proven by other users to be a flexible, accurate and powerful tool for regional modelling.

Strengths

Modular structure
Easy to drive the program from GIS-programs and the parameter estimator PEST
The model is spatial
Aquifer features can be added to the model anywhere and with any amount of detail
Water board Aa and Maas has the owner rights
Scientifically proven model

Weaknesses

No interfaces with other models
Steady-state
Less suitable for areas with a high hydraulic conductivity
High uncertainty around the leakage points
Only for free for Dutch governmental organisations
No experience with using the model for investment projects at the water board

MODFLOW

Used at Brabantse Delta and De Dommel

1. Addressed issues

Groundwater flow

2. Processes modelled

3-D ground water flow (steady and non-steady) and consequent head within confined, semi-confined and unconfined aquifers.

vertical leakage between layers.

well recharge

areal recharge (precipitation minus runoff and minus evapotranspiration)

compaction

subsidence

3. Class of models

Numerical, finite-difference, dynamic, stochastic

4. Model input

Compulsory input:

- reference heights of top and bottom of the layers
- horizontal and vertical hydraulic conductivity of each model layer
- specific head at constant pressure (C_{sat})
- transmissivity (KD-value) of a layer (confined layers)
- specific storage (if there are any transient stress periods in the simulation)
- specific yield (partially confined or unconfined layers and if there are any transient stress periods)
- saturated hydraulic conductivity (K_{sat}) (unconfined layers)
- location of impermeable boundaries
- heads at boundaries

Optional input:

- withdrawal (flow to wells)
- water inlet
- recharge from precipitation

MODFLOW formulates the groundwater flow equation without using prescribed length and time units. Any consistent units of length and time can be used when specifying the input data (Harbaugh et al., 2000). There are several graphical user interfaces available for MODFLOW in which input can be specified. The model needs data in a HDF, ASCII or binary format. The size of the data set is, depending of the area to be modelled, in the range of 1 MB to 100 MB.

5. Outputs generated

The main output variables generated are:

- groundwater level
- hydraulic head

- volumetric budget
- flow velocity
- specific discharge
- compaction of a model layer
- total subsidence
- particle position

MODFLOW generates ASCII and binary files and files are saved as such at first.

6. User possibilities

There are several graphical user interfaces available for MODFLOW (www.modflow.com):

- GMS: provides tools for every phase of a groundwater simulation including site characterisation, model development, calibration, post-processing, and visualisation.
- Visual MODFLOW Pro: possibilities for data input, simulation capabilities, model calibration and display of results.
- PMWIN: graphical pre-processor, postprocessor, automatic calibration and 3D visualisation and animation possible
- Groundwater Vistas: model design system, graphical analysis tools (displays the model design in both plan and cross-sectional views using a split window), groundwater risk assessment tool.
- Argus ONE: graphical pre-processing and post-processing software that integrates with ground-water models, GIS and work flow.

MODFLOW is easy to learn. User interaction during a run is not demanded. Because MODFLOW runs can take several hours, this would not be practical. Model output is well understandable with the graphical user interfaces. The model itself has no analytical tools, but most graphical user interfaces provide maps with contours and/or colour floods, velocity vectors, pathlines, charts, parameter sensitivity plots, profiles along a cross-section and calibration target plots. Four solver packages are included in MODFLOW (Harbaugh et al., 2000), so no external solver software is needed. Model calibration is possible with the parameter estimation package of the US Geological Survey or with PEST.

7. Modularity

The model is built up out of components, called packages and a series of highly-independent subroutines called modules (Harbaugh et al., 2000). The most frequently used packages are the recharge, the well, the river, the drain, the evapotranspiration and the streamflow routing packages. It consists of a combination of one basic package and fourteen different independent packages. These packages do not run individually but in combination with each other. They communicate by means of processes, that consist of parts of different packages, called procedures. To represent more complex features of the flow system or to improve the quality of the model, new modules or packages can be added to the program without modifying the existing ones. These modules and packages can also easily be extracted. Some tools are developed to link MODFLOW with Arc/Info (Pieterse et al., 1998), ArcView and ArcGIS. There are also a coupling with DUFLOW, called MoDuflow and some with substance transport programs like MT3D/RT3D.

8. Temporal scale

Δt = 1 day, 1 week or 1 month (usually), but may be smaller if the spatial resolution is increased

T = 1-100 years (usually, dependent of aim)

9. Spatial scale

The model is built upon a grid of rectangular cells. It is 2-D spatial for each layer.

Δx = 10-1000 m (usually)

10. Uncertainty

Assumptions made in the model are (Arnold et al., 1999):

- the use of Darcy's law
- the use of the continuity equation
- homogeneous characteristics are assumed within grid cells.
- isotropic hydraulic conductivity
- only horizontal flow in aquifers
- only vertical flow in aquitards
- above a specified elevation, evapotranspiration occurs at a maximum rate across the water table
- evapotranspiration ceases below an extinction depth
- evapotranspiration varies linearly between the depths in the 2 assumptions above
- flow is convergent toward a drain
- to get from an aquifer to a drain, water must pass through a hydraulic conductivity contrast
- there is head loss across a drain proportional to the discharge
- all streamflow entering the model is instantly available to downstream reaches during a specified time period
- leakage between streams and aquifer is instantaneous

Uncertainty analyses can be carried out with most of the user interfaces (except of Argus ONE). The numerical feature of the model limits the accuracy of the equation.

11. **Level of genericity**

The model is easily transportable to all locations. Just the input data for the model have to be known.

12. **Internal/External**

MODFLOW is used by external consultants for both water boards. It is developed by the United States Geological Survey and the United States Department of The Interior (Harbaugh et al., 2000). Water board Brabantse Delta has owner rights of the model.

13. Development status

MODFLOW is implemented and scientifically published. It has become the world-wide standard groundwater flow model. There is an extensive publicly available documentation that includes detailed explanations of physical and mathematical concepts on which the model is based and an explanation of how those concepts were incorporated in the modular structure of the computer program. One of the major limitations of MODFLOW is that it is only capable of simulating the flow and transport processes in a fully saturated system → limitations in modelling the surface hydrology and the unsaturated zone flow. The greatest limitations are those associated with representing the system as a finite-difference grid. Future developments are mainly in the coupling with other models.

14. Software code

Components of the model can easily be adapted or developed in the Fortran90 or Fortran 77 language.

15. Costs

MODFLOW can be downloaded for free from the internet (www.modflow.com). Data can be supplied by the water boards or the province of Noord-Brabant (authorisation necessary).

16. Satisfaction

Users say that there is no better model to model the effect of rivers on groundwater levels and heads.

Strengths

Many analysis tools when used in combination with GUI
No external solver software needed
Modules and packages can easily be extracted
Coupling with Arc/Info, ArcView and ArcGIS is possible
Coupling with DUFLOW available
2-D spatial for each layer
Generic
Extensive publicly available documentation
Public-domain
User satisfaction

Weaknesses

Representing the system as a finite-difference grid:
spatial discretisation is sometimes limited by data availability
error is introduced by assuming homogeneous characteristics within grid cells
MODFLOW runs can take several hours
Many assumptions made
Used by external consultants for both water boards
Limitations in modelling the surface hydrology and the unsaturated zone flow.

NAGROM

Used at Aa en Maas

1. Addressed issues

Groundwater flow

2. Processes modelled

Ground water flow (transient and steady state)

Leakage between aquifers

Seepage

Infiltration

Continues variation of the water density

3. Class of models

Dynamic, steady flow, analytic element method, deterministic, non-linear

4. Model input

Water levels in surface waters

Dimensions of water courses

Base elevation (m above sea level)

Layer thickness (m)

Hydraulic conductivity (m^2/d)

Vertical resistance c* (d)

Drainage resistance c_{drain} (d)

Precipitation residues (m/d)

Head at reference point (m above reference level)

Location of leakage points

Initial water density

The model can read ASCII DXF files. The user puts in the data by entering aquifer data and analytic elements into the input window.

5. Outputs generated

Groundwater heads (m above reference level)

Potential

Groundwater levels

Groundwater fluxes (m/d)

Flow velocity and direction

Particle position

Water density

MLAEM produces ASCII DXF files that may be read by other programs such as SURFER. Each element is stored with its topographic and geohydrologic properties. Data sets consist of small files and are maintained by using a dedicated data management system.

6. User possibilities

The model runs in NAGROM are not transparent, but the output is drawn in well-understandable plots. With available tools, the user can view the parameters of any element in the model, view co-ordinates, generate water particle traces directly and generate ten water particle pathlines that end up at the well. The model only works on the basis of acknowledged data sets and has a small calculation time. NAGROM can be coupled with a GIS like REGIS, the national geohydrological database of the Netherlands. Interfaces with MOZART, a model for the unsaturated zone with the GIS interface MONA, the drink water supply model ATLANTIS (only for input) and the ecohydrological model DEMNAT (only for output) are available. Unfortunately, no interfaces with other analysed models are available, but it should be easy to couple existing analytic elements models. It is possible to subdivide the partial models into smaller pieces.

7. Modularity

NAGROM is built up out of nine independent partial models, that run only for a specific area and can be connected with each other. These modules run individually, but some communicate with each other.

8. Temporal issues

Δt = 1 year

T = 10-100 years

9. Spatial issues

The model is spatial and calibrated for the Dutch area. Because the model uses the analytic element approach, it calculates values for certain points and no spatial resolution can be distinguished.

10. Uncertainty

The assumptions made in the model are:

- steady-state flow → retention changes in the groundwater can not be taken along in the calculations
- Dupuit-Forchheimer assumption occurs in each aquifer (vertical resistance to flow is neglected).
- the aquifers are assumed separated by initially impermeable boundaries, they are connected using leakage areas implemented by the user.
- analytic element models assume the Mass Balance Equation and Darcy’s Law as the basic equations
- aquifers are two- dimensional and isotropic

Because of the continues feature of the model, model output predicts the reality well. On the other hand, because of the many assumptions made, uncertainty increases. Uncertainty analyses by experts show that the uncertainty is considerably larger in areas with a high hydraulic conductivity than in areas with a low hydraulic conductivity. There is also a high uncertainty around the leakage points.

11. Level of genericity

NAGROM can only be applied on the Dutch area.

12. Internal/External

NAGROM is maintained, supported and distributed by the Institute for Inland Water Management and Waste Water Treatment (RIZA), the Dutch Institute for Applied Geo Sciences of TNO (NITG-TNO) and engineering company Tauw. In the case of the water board, NAGROM is run externally at TNO, but the owner rights of models are property of the water board.

13. Development status

NAGROM is documented in a series of ten partial reports for all regions. It covers 90% of the Dutch area and is designed, calibrated and documented according to one standard. In the next years, the schematisation of NAGROM will be brought into agreement with REGIS, the national geo-hydrological database of the Netherlands. The model is documented in a project plan, a system and model description, a documented code, a user manual, a management plan, an archive of model versions and a description of validation and calibration. Calibration of the model took place by linking measured values of piezometric heads and water balance. After that, hydraulic parameters, boundary head values, and infiltration and leakage values are adjusted.

14. Costs

The use of NAGROM is for free and partial models can be downloaded (www.tauw.nl/NL/producten/waterbeheer/nagrom/nagrom.htm). Just for user support, a payment has to be made. Data are available in the GIS program REGIS.

15. Satisfaction

Although the water board has little experience with the model, NAGROM has shown to be useful at national and regional scale for projects in other parts of the country.

Strengths

Dynamic model
Data sets consist of small files and calculation times are small
Many analysis tools available
Can be coupled with a GIS
Easy to couple existing models
Extensive documentation
For free

Weaknesses

High uncertainty in areas with high hydraulic conductivity
High uncertainty around leakage points
Only applicable to the Dutch area
Externally run
Not much experience at the water boards
No interfaces with other analysed models are available

SIMGRO

Used at Brabantse Delta, Aa en Maas and De Dommel

1. Addressed issues

Hydrological model for groundwater, soil moisture and surface water. Issues that are addressed are:

- Water flow
- Rainfall – runoff
- Groundwater in the saturated zone
- Groundwater in the unsaturated zone

The coupling of tools and programs for SIMGRO has led to HIB (High-water Information system Brabant). This instrument is still in use at the water boards in Brabant as a tool to search for decent areas for water storage and to analyse the effects of measures in the operational water management.

2.Processes modelled

Precipitation
Sprinkling with surface water
Sprinkling with groundwater
Evapotranspiration
Surface stream flow
Sub-soil infiltration or drainage
Capillary rise or percolation
Horizontal groundwater flow within a layer
Vertical groundwater flow between layers

3. Class of models

Stochastic, spatial dynamic, container set-up between components.

4. Model input

Basic files are made by an application in SIMGRO on the basis of internal data. Specific measures can be implemented by changing parameters in the basic files. To run the model, one needs:

Surface water system
Q-h relations
Water courses:

- Surface water depth [m]
- Drain length [m]
- Bottom width [m]
- Cotangent of side slope [-]

Sub-catchment area [m^2]
Sewered fraction of impermeable area [-]

Storage capacity of sewerage reservoir [m^3]
Place of sewer disposals
Dimensions of structures (culverts, pumping-stations, weirs and siphons) [m]
Fractional area of each type of land use (agriculture, urban, surface water, nature reserves or woodland)
% paved area in cities
% drained area in paved areas
Precipitation [mm/d]
Infiltration rate [m^3/d]
Initial evaporation [mm/d]
Topographical data:

- Land height map
- Soil map
- Geo-hydrological map

Boundary heads [m above reference level]
Land heights [m]
Hydraulic transmissivity [m^2/d]
Vertical flow resistance [d]
Layer thickness [m]
Storage coefficient [-]
Porosity [-]
Depth of root zone [m]
The model can handle ASCII-files with a specific structure. It needs large data sets.

5. Outputs generated

Groundwater head in all layers [m]
Groundwater level [m]
Groundwater fluxes [m^3/d]
Moisture content in root zone [m]
Discharges [m^3/s]
Surface water levels [m]
Latent head flux [mm]
Potential evaporation [m/d]
Actual evapotranspiration [m/d]
The model produces ASCII-files with a specific structure in which the data are saved.

6. User possibilities

The user interface Alterraqua is set-up by windows that make it possible to compute processes that are written down to ASCII-files. Interaction of the user is not necessary. The model run is not always understandable and partly documented. The model output is well-understandable and well-documented. There is a help-function available to support the user in carrying out the analytical tasks. The model has optimisation techniques that make the optimisation on the basis of computations. The model gives an indication of chanceful water storage locations. Usually, the model does not need any external solver software, but when particle traces are of importance, these can be calculated with SIMPATH.

7. Modularity

The model is set up of modules, which can be extracted, adapted and developed easy. These modules run individually, but communicate at the boundaries to make high water computations. The model can be coupled with ArcView 3.x. It is rather easy to couple SIMGRO with more detailed models like DIWA, DUFLOW and SOBEK. This handles about coupling with loose and distributed models. Fully integrated couplings with these models are still in development.

8. Temporal scale

For groundwater and unsaturated zone: daily basis, but possible to change (0.01 d – 100 d).

T = 50 years

For surface water: 0,5-2 hour. Also the interaction between ground- and surface water is calculated for this small time step. The time horizon can be chosen. A model run for an event takes 5 minutes. A model run for a map of inundation changes takes 8 hours.

9. Spatial scale

The model is spatial with an output resolution of 25 m and a maximum number of 1000 subcatchments. For the groundwater modules the density of calculation points can be increased. For the unsaturated zone, Δz = 0,10 m.

10. Uncertainty

A schematisation in aquifers and aquitards is applied. The area to be modelled is divided into a number of finite elements with knots. In an aquifer, there is only horizontal flow and in an aquitard, there is only vertical flow. The assumption is made that the second and third soil layers have no influence on the surface water model. The uncertainty depends of the spatial scale which one wants to observe. On regional scale, the model is okay. On local scale, it is not okay, so it is not possible to make decisions at parcel scale. It is only possible to put in grids where all mash sizes are the same within each grid.

11. Level of genericity

The model is mainly suitable for the Netherlands.

12. Internal/External

The model is run internal at all water boards. The water boards have the owner rights of the model. Also, Aa en Maas has the owner rights of there own build models and the rights of externally build models belong the water board. The model is built by Alterra in Wageningen, the Netherlands in co-operation with engineering company Grontmij (www.alterra.wur.nl/NL/prodpubl/modellen/simgro).

13. Development status

SIMGRO is implemented and already used at all participating Dutch water boards, especially as decision support for the dimensioning of water retention. Aa en Maas is building 4 models with it, that are still in a conceptual stage. Although it is scientifically accepted, it is still being improved. It has a technical specification, but no specific document at the moment. In the future, a one way direction coupling with SOBEK will be available and it also will be possible to make grids where the mash sizes within each grid are not all the same. When SIMGRO models are calibrated, the hydrologic parameters are not always correct. For instance: drainage and infiltration resistance have less influence on the result, but the daily distribution of the precipitation has.

14. Software code

Components can be adapted and developed easy in ASCII-files. The implementation language of the software code is Fortran.

15. Costs

SIMGRO is for free and also new versions are for free. At Brabantse Delta and Aa en Maas, a cost-benefit analysis was carried out before model application. At Brabantse Delta, every time the decision is made whether to use the free SIMGRO or the commercial SOBEK. At Aa en Maas, estimations of the costs of model use are made. These costs can differ strongly. The water boards are supplying most of the data, but for soil carts, vegetation carts, geomorphologic carts and precipitation data it is necessary to pay.

16. Satisfaction

Water board Brabantse Delta is satisfied of the results for sandy areas with a low slope but not for flat polder areas. Aa en Maas is not satisfied at the moment but expects that this will change in the future. Both water boards think it can be of use for nofdp when the (known) problems with the model are solved.

Strengths

Suitable for making regional policy
Is still being improved
For free
Future interfaces with SOBEK, DUFLOW and MODFLOW
The model is set up of modules, which can be extracted, adapted and developed easy
The water boards have the owner rights of the model

Weaknesses

Not user friendly
Mainly suitable for Dutch situation
Not suitable on parcel scale
SIMGRO needs large datasets
For calculating particle traces, the model needs solver software

SOBEK-CF

Used at Brabantse Delta, Aa en Maas and De Dommel

1. Addressed issues

Channel flow

2. Processes modelled

1D transient water flow through a channel

3. Class of models

Dynamic, physical-deterministic

4. Model input

Boundary conditions:

- Initial water level [m above reference level] or
- Initial water depth [m] or
- Initial discharge [m^3/s] or
- Q-h relation

Network:

- Shape of the network
- Lateral inflow [m^3/s]
- Bed level [m above reference level]
- Surface level [m above reference level]
- Shape of cross sections
- Bed friction [C, mn, kn, ks, kn,]

Optional:

- Artificial structures
- Constant seepage/infiltration [mm/s]

The model can handle ASCII files like .shp with a specific composition.

5. Outputs generated

- Water levels [m above reference level]
- Water depths [m]
- Freeboard [m]
- Discharge [m^3/s]
- Flow velocity [m/s]
- Water level gradient
- Head [m]

Outputs are generated in ASCII- or Excel-format and can be saved in a data base (GIS- or CAD-environment) or in ASCII-files.

6. User possibilities

The user interface is set up of windows in which processes can be computed by the steps input→computation→presentation. User interaction is not necessary. The model run and the output are understandable and well-documented. A help-function is available. The model has no direct techniques to choose the best measure (the user has to do this on the basis of the model results), but the model gives enough support for decision making. It does not need special extern solver software. A model run can take any time between a few seconds and several days. In the example of the Tongelreep it took 5 minutes in combination with the rainfall-runoff module (static run). In 1999 an extensive research project was started to speed the computation time of the simulation package SOBEK. It is expected that the computations will be accelerated with a factor 100, by using multi-processor computers (www.sobek.nl/News/releases.html).

7. Modularity

SOBEK-CF itself is a module of SOBEK. It can run individual or in combination with other modules and is not easy to extract, adapt or develop, because it is very complex. It is not composed itself. It can communicate with other modules at knots and water streams. SOBEK reads all standard GIS formats. SOBEK-CF interfaces completely with all other SOBEK modules. There are no interfaces with other models, but in the future, there will be a one way direction coupling with SIMGRO. Consultancy company Hydrologic has made some useful couplings to convert SOBEK-CF schematisations into DUFLOW-quantity schematisations.

8. Temporal issues

The user can choose between every temporal scale. The time scale for hydrodynamic processes lies in the order of minutes to even seconds. For most computations, a time step of 10 minutes should be sufficient, but for river systems with a very quick respond-time (such as mountain streams), a smaller time step might be more appropriate. The time horizon is a number of years.

9. Spatial issues

Local scale (in practice 100 m); it is also possible to model at regional scale. The model is not-spatial (1-D), but can be spatialised easy by projecting water levels above the height map.

10. Uncertainty

SOBEK is based upon the complete set of Saint Venant Equations. The assumption is made that these equations are true at all places and time steps. The model is also useful at local scale.

11. Level of genericity

The model can be applied everywhere.

12. Internal/External

The model is run internal at all water boards together with the rainfall-runoff module to compute the need for retention. It is built by WL Delft in the Netherlands (www.sobek.nl). The water boards have the owner rights of the model and the models that are self-made with SOBEK. When models are built externally, the owner rights will go to the water board.

13. Development status

The model is already implemented and scientifically accepted, though it is still in development. Calibration and validation take place on the basis of water levels and discharges. There are a manual and a website available and for problems, a helpdesk can be called. At the moment, a coupling is made with SIMGRO to make a ground-water-surface water model. Another development is the incorporation of SOBEK into the GF and the OpenMI (Blind et al., 2001).

14. Costs

The software is commercial. The water board is supplying most of the data, but for soil maps, vegetation maps, geomorphologic maps and precipitation data it is necessary to pay.

15. Satisfaction

All water boards are satisfied about SOBEK, especially compared to other models, but also said that it is still in development. They all think that SOBEK itself and the coupling between SOBEK and SIMGRO can be used for nofdp to give input to other models.

Strengths

Allows for a stable and robust computation.
The model is very suitable on a local scale.
By the section geo-information of the Brabantse Delta water board, a coupling of output with GIS is made.
In the future, there will be a one way direction coupling with SIMGRO.
Within the water boards, there is a lot of experience from former projects
Outputs of and processes within the model are well documented.
All the water boards have owner rights for SOBEK.

Weaknesses

There are no interfaces with other models at the moment
The expensive license
The difficulty of adapting and rebuilding the module

SOBEK-RR
Used at Brabantse Delta, Aa en Maas and De Dommel

1. Addressed issues

Rainfall – runoff

2. Processes modelled

Rainfall
Surface run-off
Sub-soil drainage
Evapotranspiration
Capillary rise
Seepage
Infiltration (surface water)
Percolation

3. Class of models

Dynamic and physical deterministic

4. Model input

The input data are available at the water boards, but a schematisation has to be made in the model software. The following input is necessary to run the model:

- Relationship between discharge and water level
- Area per crop [m^2, ha or km^2]
- Surface levels [m above reference level]
- Soil type
- Initial groundwater level [m below surface level]
- Infiltration capacity [mm/hr or mm/day]
- Drainage resistance values for each layer [day]
- Soil storage coefficient
- Downstream water level [m above reference level]
- Seepage [mm/day]
- Surface of paved area [m^2, ha or km^2]
- Capacity of sewer pumps [mm/hr, m^3/min or m^3/hr]
- Inhabitants
- Water use per inhabitant [m^3/day, l/hr or l/day]
- Maximum storage capacities of the street level and the sewer system [mm or m^3]
- Water level at boundary of the model [m above reference level]
- Bottom level of open water [m above reference level]
- Area of the open water [m^2, ha or km^2]
- Target level is being maintained by weirs or other structures [m above reference level]
- Hydraulic friction of a channel [$s/m^{1/3}$]

- Channel length [m]
- Bottom width of a channel [m]
- Slope of a channel
- For weirs: discharge coefficient, width [m], initial crest level [m above reference level]
- For orifices: Discharge coefficient c, contraction coefficient, width [m], crest level [m above reference level], initial gate opening [m]
- Pump station capacity [m^3/s , m^3/min or m^3/hr]
- Amount of water that is extracted from the system and amount of water that is injected into the system by industry

The model can handle ASCII .shp files with a specific composition. It needs data sets of about 1 CD-ROM.

5. Outputs generated

- Discharges [m^3/s]
- Water levels [m]
- Open water volume [m^3]
- Storage [mm]
- Spilling [m^3/s]
- Pumped flow [m^3/s]
- $Q_{open\ water}$ [m^3/s]

Outputs are generated in ASCII- or Excel-format and can be saved in a data base (GIS- or CAD-environment) or in ASCII-files.

6. User possibilities

The user interface is set up of windows in which processes can be computed by the steps input→computation→presentation. User interaction is not necessary. The model run and the output are understandable and well-documented. A help-function is available. The model has no direct techniques to choose the best measure (the user has to do this on the basis of the model results), but the model gives enough support for decision making. It does not need special extern solver software.

7. Modularity

SOBEK-RR itself is a module of SOBEK. It runs individually and is not possible to extract, adapt or develop, because it is too complex. The structure of the framework is based on 5 compartments: atmosphere, surface level, unsaturated zone, saturated zone and groundwater (www.niwi.knaw.nl/nl/oi/ict/atmosfeer/OND1300798). It can communicate with other modules by knots and water streams. The model integrates with all standard GIS. SOBEK-RR interfaces completely with all other modules. There are no interfaces with other models, but in the future, there will be a one way direction coupling with SIMGRO.

8. Temporal issues

The user can choose between every temporal scale. The time horizon is a number of years. A model run can take any time between a few seconds to several days. In the example of the Tongelreep it took 5 minutes (static run) in combination with the channel flow module.

9. Spatial issues

The module is spatial. Catchment areas can easily be modelled in a lumped or detailed manner, with no restriction to the number of catchment areas. Catchment areas can be modelled in any detail using land elevation curves, soil characteristics, land cultivation, drainage characteristics etc.

10. Uncertainty

SOBEK is based upon the complete set of Saint Venant Equations. The assumption is made that these equations are true at all places and time steps. Most of the attention is given to hydraulical processes. The uncertainty in the model depends of the subject of the model study and the uncertainty in the input data. The model is also useful at local scale.

11. Level of genericity

The model can be applied everywhere.

12. Internal/External

The model is run internal at all water boards together with the channel flow module to compute the need for retention. It is built by WL Delft in the Netherlands (www.sobek.nl). The water boards have the owner rights of the model and the models that are self-made with SOBEK. When models are built externally, the owner rights will go to the water board.

13. Development status

The model is already implemented and scientifically accepted, though it is still in development. Calibration and validation take place on the basis of water levels and discharges. There are a manual and a website available and for problems, a helpdesk can be called.

14. Costs

The software is commercial. At Aa en Maas a cost-benefit analysis was carried out. At De Dommel it was not known how the choice was made for SOBEK, but it did not seem that a cost-benefit analysis was carried out. At Aa en Maas, the costs for model use are estimated, but at De Dommel it was only known when the modelling work was done externally. The water board is supplying most of the data, but for soil maps, vegetation maps, geomorphologic maps and precipitation data it is necessary to pay.

15. Satisfaction

All water boards are satisfied about SOBEK, especially compared to other models, but also said that it is still in development. They all think that SOBEK itself and the coupling between SOBEK and SIMGRO can be used for nofdp to give input to other models.

Strengths

Detailed, so very useful at local scale

At the moment, a one way direction coupling with SIMGRO is built

Experience at water boards for Bovenmark, city of Den Bosch and Tongelreep
From the documentation it is clear how the model processes its information
The module is dynamic
All water boards have owner rights of SOBEK
Coupling with standard GIS possible

Weaknesses
No water quality
Commercial software
Not easy to extract, adapt or develop

Waterdoelen

Used at province Noord-Brabant

1. Addressed issues

Groundwater flow

2. Processes modelled

Groundwater level fluxes

Groundwater flow fluxes

3. Class of models

Deterministic, dynamic

4. Model input

Input parameters:

- Reference heights of top and bottom of the layers
- Hydraulic conductivity
- Surface level
- Dimensions of the drainage system
- Land use
- Precipitation
- Evapotranspiration
- Withdrawals

Research for soil parameters and ground water levels is necessary. All other data are available at the province. It is possible to indicate measures in a grid. The model needs data sets of 1-100 MB (for Noord-Brabant) with ASCII files. For other types of files, an interface is necessary.

5. Outputs generated

Output parameters:

- Groundwater fluxes
- Groundwater heads

In the first instance, data are saved in ASCII files. To use the output as input for other models, interfaces are necessary.

6. User possibilities

A MODFLOW interface is used. User interaction during a run is not optional or demanded. The model run and its output are understandable and clearly documented. Analytical tools of the user interface can be used to carry out analytical tasks. The model has techniques to compare the model results with the water demands of the various functions and to assess the realisation of the water aims (100% succeeded, 0% not succeeded, between 0-100% almost succeeded). It does not need any external solver software. The model has no GIS-tools, but ArcView and ArcGIS files can be imported. There are no interfaces with other models. The Waterdoelen model gives a useful support when taking decisions for the planning of investment projects.

7. Modularity

The model is built up out of relative independent components. These components are read in apart, but run together to find a solution. It is easy to extract these components.

8. Temporal issues

Δt = freely adjustable, generally one week

T = infinite

9. Spatial issues

The model is spatial.

Δx = 250 x 250 m

9 layers

10. Uncertainty

The assumptions made in the model are:

- The use of Darcy's law
- The use of the continuity equation
- Homogeneous characteristics are assumed within grid cells.
- Isotropic hydraulic conductivity
- Flow in aquifers is horizontal.
- Flow in aquitards is vertical.
- Above a specified elevation, evapotranspiration occurs at a maximum rate across the water table
- Evapotranspiration ceases below an extinction depth
- Evapotranspiration varies linearly between the depths in the 2 assumptions above
- Flow is convergent toward a drain
- To get from an aquifer to a drain, water must pass through a hydraulic conductivity contrast
- There is head loss across a drain proportional to the discharge
- All streamflow entering the model is instantly available to downstream reaches during a specified time period
- Leakage between streams and aquifer is instantaneous

The uncertainties in the results are tolerable, 20 to 30 cm accuracy.

11. Level of genericity

The model is built for the region of Noord-Brabant, but the principles of the model can be transferred to other areas.

12. Internal/External

The model is run by research institute TNO. The MODFLOW instrument is developed by the United States Geological Survey and the United States Department of The Interior and some parts of the Waterdoelen model are developed by TNO. The province has the owner rights and the intellectual knowledge is at TNO.

13. Development status

Since 1995, the model is used in support of the policy for the implementation of the Reconstruction Law Concentration Areas Stock Farming. There are no articles written about the model, but it has been presented at a congress. Documentation is available in three reports. The model is calibrated with the representer method. With this method, one defines a number of measure points and the model will automatically adapt. Data of Noord-Brabant were used. In the future, a bigger accuracy is tried to be obtained with the use of a finer grid.

14. Software code

It is easy to adapt or develop the model in the implementation language Fortran.

15. Costs

MODFLOW can be downloaded for free from the internet. For the use of the Waterdoelen model, authorisation of the province is necessary, but the use will be for free. The basic files for the model are not delivered with the model. Authorisation of the province is necessary for the use of them.

16. Satisfaction

Users are satisfied about the use of the model. The developer does not know if the model can be of use for the IDSS, but think that there is no better model to simulate the effects of groundwater and surface water on each other.

Strengths

Dynamic model
Model run and output are understandable and clearly documented
Analytical tools can be used to carry out analytical tasks
Techniques to compare model results with water demands of various functions and to assess the realisation of water aims are available with the model
Does not need external solver software
ArcView and ArcGIS files can be imported
Easy to extract components
Spatial model
Documentation is available in three reports
In the future, higher accuracy by using a finer grid
Use is for free

Weaknesses

Research for soil parameters and ground water levels is necessary
No GIS-tools available within the model
No interfaces with other models
Many assumptions made
Built only for the region of Noord-Brabant
Run externally
Not scientifically accepted

Appendix H: Selection criteria

End-user criteria

The nofdp IDSS, as a practical policy making aid, requires that much of the development is constrained on ensuring that the system is easy to use by the end-users. Such focus is generally not the object of scientific, research-based modelling so it is important that the end-user requirements of a policy-relevant model-based IDSS are carefully defined and met by all models. This is achieved through the use of nine criteria:

1. All processes

Representations of domain processes employed by the models must be sufficient to provide the outputs required by the end-user.

2. Input

A model should use common measured input parameters.

3. Output

Each model should produce high quality output of use to the end-users.

4. User friendliness

Each model should be fast and working with the IDSS should be easy. Clever models, fast algorithms and an efficient software code are required to achieve this. Models should read all standard GIS-formats.

5. Genericity

It should be possible to transfer the models to other areas.

6. Temporal issues

Models should have a temporal resolution that reflects the scale of variation in the most important variables and should have a time horizon that is relevant for policy design.

7. Spatial issues

The models should run on one of the two spatial scales. They should have a spatial resolution that reflects the scale of variation in the most important variables.

8. Satisfaction

Users of the models should be satisfied with the use of them and give a positive suggestion for implementation into the IDSS.

9. Transparency

Users should be able to understand the way in which the model processes its information.

Scientific criteria

Scientific criteria deal with what can and what cannot be integrated from a scientific point of view. It involves constraints on the type of models, on the temporal dynamics and time scales, on the spatial dynamics and spatial resolutions, on the details that matter and on rigorous methods for aggregation and simplification. Five scientific criteria were formulated:

1. Models fitting the integration scheme

Models should have logical connections with other models that are input- or output-connected. They should fulfil a specific task not dealt with by any other model.

2. Temporal issues

Dynamic models are preferred. Models should have a temporal resolution that reflects the scale of variation in the most important variables and should have a time horizon that is relevant for policy design.

3. Spatial issues

Only spatial models or models that can be spatialised should be integrated. The models should run on one of the two spatial scales. They should have a spatial resolution that reflects the scale of variation in the most important variables.

4. Compatibility of scientific paradigms

The scientific paradigm of a model should be compatible with those of other models.

5. Scientifically proven

A well understood and proven model is preferred above a new, poorly documented and less proven one.

Technical criteria

To ensure that all selected models can be integrated into an efficient operating IDSS, five technical criteria were applied to the candidate models:

1. Modularity

When models consist of relatively independent components, it has to be possible to take these components out easily.

2. Flexibility

Models should be implemented in a source code that makes it easy to adapt or develop them, possibly after sub-division into smaller parts.

3. Data

Models should not need too large data sets and should handle the type of data that are generated by other models.

4. External solver-software

Models should not need too much external solver-software.

5. Compatibility

It should be possible to couple the model with other models by means of interfaces or an application framework.

Organisational criteria

Finally, four organisational criteria, that have to assess the models for their organisational availability for the project, are formulated. These criteria can be of use when attempting to decrease the costs of the use of models and data.

1. Documentation

Well-documented models are preferred above poorly-documented models.

2. Owner rights

The owner rights of the models should be in hands of the project partners as much as possible.

3. Costs

Freeware and open source models are preferred.

4. Future developments

When models have deficits, future improvements can overcome these.

Table H-1 details the relationships between the set of model characteristics and the selection criteria. The left hand column is filled with the model characteristics of the model description forms and the upper row with the selection criteria. When a cross is put in a cell, it means that the information about the corresponding characteristic is used to assess if a model fits the corresponding criterion. E.g. information about the possibilities of a model are used to assess the user friendliness of that model.

Table H-1: Model characteristics – selection criteria impact table

Model charac-teristic	**End-user criteria**									**Scientific crit.**					**Technical crit.**					**Organisat.**			
	Processes	Input	Output	User friendly	Genericity	Time issues	Space issues	Satisfaction	Transparent	Fitting	Time issues	Space issues	Compatible	Proven	Modular	Flexible	Data	Solvers	Compatible	Documents	Ownership	Costs	Development
Processes	x																						
Model class											x												
Model input		x								x							x						
Output			x							x							x						
Possibilities				x					x									x	x	x			
Modularity															x								
Time issues				x		x					x												
Spatial							x					x											
Uncertainty													x										
Genericity					x																		
Inter-nal/External									x												x		
Develop-ment status														x					x	x			x
Software code				x												x							
Costs																						x	
Satisfaction				x				x															

Appendix I: Expected value method

The expected value method as suggested by Nijkamp et al. (1990), provides a way of transforming qualitative scores to quantitative values on the basis of a non-linear distribution. When using the expected value method, qualitative scores are quantified in the following way:

- $v_{best} = 1$
- $v_{second\ best} = 1 - \frac{1}{m^2}$
- $v_{third\ best} = 1 - \frac{2}{m^2} - \frac{1}{m(m-1)}$
- $v_{fourth\ best} = 1 - \frac{3}{m^2} - \frac{2}{m(m-1)} - \frac{1}{m(m-2)}$
- etc.

In this case, v is the quantitative score on the criterion and m is the number of models that is compared with each other.

In more or less the same way, the weights that belong to the different types of criteria are determined:

- $w_{lowest} = \frac{1}{c^2}$
- $w_{second\ lowest} = \frac{1}{c^2} + \frac{1}{c(c-1)}$
- $w_{third\ lowest} = \frac{1}{c^2} + \frac{1}{c(c-1)} + \frac{1}{c(c-2)}$
- etc.

In this case, w is the weight of the type of criteria and c is the number of types of criteria used.

For the model selection, the ranking of the models for a specific type of criteria (e.g. end-user, scientific, technical or organisational) was done in an informal way. Afterwards, the quantitative score for each model at that specific type of criteria was determined. The types of criteria were given weights, assuming the following order of importance:

1. End-user criteria, $w_1 = 0.52$
2. Scientific criteria, $w_2 = 0.27$
3. Technical criteria, $w_3 = 0.15$
4. Organisational criteria, $w_4 = 0.06$

Finally, the total score V for model i can be calculated with the following formula:

$$V_i = \sum_{j=1}^{4} w_j v_{ij} \qquad (1)$$

with w_j the weight of criterion j and v_{ij} the value for model i on criterion j. The model with the highest total score should be the most suitable one.

Appendix J: Selection processes

Rainfall-runoff models

End-user criteria

All processes

SIMGRO is the only model with which sprinkling with surface and groundwater can be modelled. It is also the only model that models extensive groundwater flows. HYBNAT models the fewest processes. It does not model evapotranspiration, percolation and capillary rise. Also DUFLOW-RAM does not model capillary rise, but it is the only model that generates water quality data for runoff. So it is only possible to model diffuse sources with DUFLOW-RAM.

Input

HYBNAT uses common input parameters. DUFLOW-RAM needs some parameters of unpaved areas and seepage that are not very commonly measured. SIMGRO needs parameters of initial infiltration and initial evaporation. Also, SOBEK-RR needs some uncommon input parameters.

Output

All models and modules generate a runoff that could serve as an input for hydraulical models.

User friendliness

HYBNAT has no user interface, but can make fast calculations (a few seconds). DUFLOW-RAM and SOBEK-RR calculations take longer (a few minutes up to one hour). SIMGRO calculations take longer then those of the other models. Except of HYBNAT, there are help functions available for all models. Only SOBEK can read all standard GIS-formats.

Genericity

DUFLOW-RAM and SOBEK-RR are generic modules. HYBNAT is not suited for mountainous areas and for calculating extreme floods. SIMGRO is mainly suitable for the Netherlands.

Temporal issues

With all models, temporal scales can be chosen that reflect processes at both levels of detail.

Spatial issues

DUFLOW-RAM, HYBNAT and SOBEK-RR all model processes at a catchment scale. SIMGRO generates output with a mesh size of 25 m. Because of this detailed output, calculation time can be long.

Satisfaction

The water boards are satisfied of DUFLOW-RAM, HYBNAT and SOBEK-RR. They are less satisfied about SIMGRO, but think that future developments will improve the model. Also the coupling between SIMGRO and SOBEK can be of interest for the IDSS.

Transparency

None of the models is transparent.

Sub-conclusion

DUFLOW-RAM is the only module that takes water quality into account and because of that, it gets the highest score. SOBEK-RR is second best as its possibilities of reading all standard GIS-formats makes it more user friendly, but because it also do not able the user to model diffuse pollutant sources. HYBNAT is third best, because it is not as user friendly as the thirst two models (e.g. no GIS-coupling possibilities), but it uses more common parameters then SIMGRO, has shorter calculation times and has a higher user satisfaction.

Scientific criteria

Models fitting the integration scheme

All models model the process that lies between precipitation and runoff that can serve as input for hydraulic models. DUFLOW-RAM is the only module in which diffuse pollutant sources can be modelled directly.

Temporal issues

All models are dynamic. The minimum time step SIMGRO uses (30 minutes) can be too long for the riverine processes SOBEK-CF models (time step 10 minutes).

Spatial issues

All models are spatial or can be spatialised. All models generate runoffs that can be an input for the hydraulic model at specific points (e.g. mouth of tributaries).

Compatibility of scientific paradigms

All models have a non-steady character and are based on the equations of mass and impulse balance. They all use a reservoir approach to a more or less extend (groundwater or modelling of water streams).

Scientifically proven

All models are scientifically proven and well understood.

Sub-conclusion

Again, SOBEK-RR and DUFLOW-RAM have the best results. They can meet the demands of hydraulical models and are dynamic. Because it is likely that the SOBEK-CF module will be advised for the hydraulical part of the IDSS, SOBEK-RR is preferred over DUFLOW-RAM, but this can change when SOBEK appears to have coupling problems. HYBNAT in turn, is better then SIMGRO because more time steps can be chosen.

Technical criteria

Modularity

As contrasted with the other models, it is impossible for the user to extract and adapt SOBEK modules by itself. (Expensive) help of WL Delft is necessary.

Flexibility

HYBNAT and SIMGRO are easy to develop in Fortran. The implementation language of DUFLOW is also based on Fortran, but is less current. The implementation language of SOBEK is unknown.

Data

All models can read and generate ASCII files.

External solver-software

For the aims of the rainfall-runoff model, none of the models and modules needs external solver software.

Compatibility

In the near future, couplings of SIMGRO with SOBEK, DUFLOW and MODFLOW will be made. SOBEK-RR can be linked with SOBEK-CF in an easy way. DUFLOW has an interface with MODFLOW, but can be coupled with SOBEK in the future by means of the Generic Framework. HYBNAT has no interfaces with other models that are evaluated in this study.

Sub-conclusion
SIMGRO is likely to be the model that will be the easiest to integrate into the IDSS. It is open source and when the future interface with SOBEK is ready, it is easy to couple the rainfall-runoff and hydraulic model with each other. DUFLOW-RAM is second best. It is open source and with the Generic Framework it will be easy to couple it with SOBEK-CF. SOBEK is third. Although it is not open source and adaptations are expensive, it can already be linked with SOBEK-CF in a simple manner. HYBNAT is the least suited for technical integration, because it has no interfaces with other evaluated models at all.

Organisational criteria

Documentation
SOBEK and DUFLOW both have a users guide available. For SOBEK, also a help-desk can be called. SIMGRO only has a technical specification, but no specific document. For HYBNAT, only a short description is available at the water board.

Owner rights
For DUFLOW, SIMGRO and SOBEK, the water boards have the owner rights of the models. For the use of HYBNAT, authorisation of Brandt Gerdes Sitzmann is necessary.

Costs
SIMGRO is for free and also new versions are for free. HYBNAT is sold to universities and institutes in individual cases. DUFLOW-RAM can be obtained for free, but for user support and updates, a licence of 295 Euro/year has to be bought. For SOBEK, an expensive licence has to be bought and also for adaptations to the model, a payment has to be made. At the moment however, a project licence for SOBEK is bought what would make the investment for the purchase of DUFLOW redundant.

Future developments
DUFLOW will be incorporated into the Generic Framework. For HYBNAT, there are no major developments on the stocks. In the future, couplings of SIMGRO with SOBEK (currently developed), DUFLOW and MODFLOW should be possible and it also will be possible to make grids where the mash sizes within each grid are not all the same. Next to the coupling with SIMGRO, also SOBEK will be incorporated into the OpenMI.

Sub-conclusions
SIMGRO has the best organisational circumstances for implementation. It is freeware, and many couplings with other models are or will be developed. The DU-

FLOW-RAM module is second best as it is no freeware but open source. HYBNAT fits the organisational criteria slightly less good, because it has less documentation and will not be migrated to the OpenMI in the long term. SOBEK-RR is neither freeware nor open source so it totally does not fit the organisational criteria .

Ranking of the models

In table J-1, the ranking for the different rainfall-runoff models is given.

Table J-1: Ranking of the rainfall-runoff models

	DUFLOW-RAM	**HYBNAT**	**SIMGRO**	**SOBEK-RR**	**Weights**
End-user criteria	1.00	0.79	0.52	0.94	0.52
Scientific criteria	0.94	0.79	0.52	1.00	0.27
Technical criteria	0.94	0.52	1.00	0.79	0.15
Organisational criteria	0.94	0.79	1.00	0.52	0.06
	0.971	0.750	0.621	0.909	

As can seen, DUFLOW-RAM and SOBEK-RR are much more suitable for incorporation into the IDSS then HYBNAT and SIMGRO. The score difference of 0.062 points is small what points to the suitability of both modules as possible model for the IDSS. However, DUFLOW-RAM seems the most suited model as it models water quality, that seems to be a very important factor in the IDSS. The water quality that is generated by the rainfall-runoff module, can be translated by the water quality model of the channel flow and the solute transport module of the groundwater model into a quality of the soil moisture that seems of large influence on the vegetation. Finally, it has to be stated that all models are very good models and that differences between the models are not very large. HYBNAT and SIMGRO may have a score that is much lower then that of the other two models, but this is mainly the result of the lack of user friendliness of both models and of the lack of coupling possibilities of HYBNAT. SIMGRO may be of use for the IDSS when the coupling with SOBEK is ready.

Hydraulic models

Note: Only DUFLOW-quantity and SOBEK-CF are compared with each other because DIWA has been integrated into SOBEK in 1998, nowadays has been replaced by DUFLOW on its application domain and is dissuaded by the water board Brabantse Delta.

End-user criteria

All processes
Both models model the same process, i.e. unsteady (transient) flow.

Input
SOBEK has more options to input roughness and cross sections. Whereas DUFLOW assumes a trapezium shaped cross profile, SOBEK can handle twelve types of cross section shapes. Disadvantage of SOBEK is that it needs some less routinely measured data as the depth of the profile affected by the sediment transport and grain sizes.

Output
Outputs generated by both models are more or less the same.

User friendliness
By using the multi processor computers, SOBEK will be able to make much faster calculations of extensive flow networks than DUFLOW. SOBEK is also the only model that can read all standard GIS-formats. With both models it is easy to make simple schematisations in little time and for problems, a helpdesk can be called.

Genericity
Both models are generic.

Temporal issues
Both models are able to represent processes on time scales and for time horizons that seem suitable for the two levels of scale that are incorporated into the IDSS.

Spatial issues
Both models are able to model spatial scales and time horizons that seem suitable for the two levels of scale that are incorporated into the IDSS.

Satisfaction

Users are in generally more satisfied about SOBEK than they are about DUFLOW, especially for modelling large networks. That is the reason why SOBEK is the most current model.

Transparency

Both models have a user guide and a help function that document the processes of the model in an understandable way.

Sub-conclusion

Although both models are suitable for policy making, SOBEK fits the end-user criteria just a bit better then DUFLOW. Users have more possibilities in designing flow channels, SOBEK will make faster calculations in the future, it can read all standard GIS formats and user satisfaction is higher.

Scientific criteria

Models fitting the integration scheme

Both models can be used to translate runoffs as calculated by the rainfall-runoff models to water levels and flow velocities that can act as input for water quality, groundwater or ecological models.

Temporal issues

Both models are dynamic. Because with both models temporal resolutions can easily be adapted to those of other models, internal consistency is secured.

Spatial issues

Both models are not spatial and can reflect processes on the necessary spatial scales.

Compatibility of scientific paradigms

Underlying scientific paradigms are the same for both models.

Scientifically proven

Both models are scientifically accepted.

Sub-conclusion

Because both models are structured in more or less the same way, they both fit the scientific criteria to the same, very large, amount.

Technical criteria

Modularity
It is much easier to extract, adapt and develop the quantity module of DUFLOW, then the channel flow module of SOBEK, although the latter can run individually when necessary.

Flexibility
The language of the software code of SOBEK is unknown. Because the code is not open source it is impossible to adapt SOBEK by yourself. So its flexibility is negligible compared to that of DUFLOW.

Data
Both models can read and produce ASCII files.

External solver-software
SOBEK does not need any external solver software. It is not known if DUFLOW needs external solver software.

Compatibility
At the moment, SOBEK has no interfaces with other models. In the future, an interface with SIMGRO will be available. DUFLOW has an interface with MODFLOW. Both models can exchange information with GIS programs.

Sub-conclusion
DUFLOW meets the technical criteria better then SOBEK does. Both models can read and produce the same type of files and have an interface with another potential available model, but DUFLOW is much easier to adapt and develop.

Organisational criteria

Documentation
Both models are well-documented. Users guides and help functions are available.

Owner rights
All water boards have a SOBEK licence and Brabantse Delta has a DUFLOW licence. When models are made with the programs, the water boards keeps the owner rights and when models are built external, the water board buys the owner rights.

Costs

For both models, a licence has to be bought. The purchase of DUFLOW is for free for STOWA members and user support and updates can be obtained at 795 Euro/year. The licence costs for SOBEK, on the other hand, are much higher.

Future developments

Both models will be incorporated into the Generic Framework. Also a coupling between SOBEK and the rainfall-runoff model SIMGRO will be made.

Sub-conclusion

For both models, enough documentation is available and owner rights are within the water boards. In addition, both models will be coupled with other models in the future. The major difference between the models are the licence costs, that are higher for SOBEK.

Ranking the models

In table J-2, the ranking for the different hydraulic models is given.

Table J-2: Ranking of the hydraulic models

	DUFLOW-quantity	**SOBEK-CF**	**Weights**
End-user criteria	0.75	1.00	0.52
Scientific criteria	0.875	0.875	0.27
Technical criteria	1.00	0.75	0.15
Organisational criteria	1.00	0.75	0.06
	0.836	0.914	

So, the conclusion can be drawn that SOBEK-CF is more suited for integration into the IDSS. This does not mean that SOBEK-CF is automatically integrated. Especially the possibility to couple DUFLOW with MODFLOW makes DUFLOW an interesting option when integration of SOBEK would not be possible.

Groundwater models for the saturated zone

Note: To simplify the selection process, only the model instruments MLAEM, MODFLOW and SIMGRO are observed. The NAGROM and Waterdoelen models are only used as examples of model applications.

End-user criteria

All processes
MODFLOW and SIMGRO model the same processes in nearly the same way. MLAEM models in a different way, so that flow between layers can only be modelled with infiltration points. With MLAEM it is possible to model density variations, contrasted with MODFLOW and SIMGRO. Advantage of MODFLOW is that is can simulate calculated compaction and subsidence (defined as the sum of all compactions), which makes it especially suitable for projects in the western part of the Netherlands.

Input
In MODFLOW and SIMGRO, input data for aquifers are common values such as transmissivities, aquitard resistances, groundwater recharges, surface water levels, etc. In MLAEM sometimes less common parameters such as the resistance to flow, total discharge or head distribution along the analytical elements need to be specified.

Output
Only with MODFLOW, compaction and subsidence can be calculated, which can be interesting for policy making. Only MLAEM enables the user to model density fluctuations.

User friendliness
Whereas MODFLOW often has long simulation runs, it is easy to shorten the calculation time with MLAEM and SIMGRO by removing elements or changing the grid structure. This is at the expense of the quality of the output. With MLAEM, more input there are more input possibilities but implementing for example structures is less easy then in MODFLOW and SIMGRO. With SIMGRO, it is only possible to put in grids where all mash sizes are the same within each grid. MLAEM and MODFLOW do not use external solver software, but for SIMGRO, an extra solver is needed to calculate pathlines.

Genericity

Whereas MLAEM is less suitable in areas with a high hydraulic conductivity like sandy soils, SIMGRO is only suitable for the Dutch situation. MODFLOW gives good results for all types of soils in all areas.

Temporal issues

All models have temporal resolutions (month, year) and time horizons (100 years) that seem suitable for policy making.

Spatial issues

The possible spatial resolutions of MODFLOW (10-1000 m) are suitable for both regional policy making and local issues. The resolution of SIMGRO (25 m) can be too coarse for local problems. MLAEM uses a different method of spatialising and cannot be compared with the other two models. Because the analytic element method assumes aquifers of infinite size, it seems unsuitable for the local scale of the IDSS.

Satisfaction

At the moment, the water boards are not satisfied with SIMGRO, but think this will change when future developments are implemented. For groundwater modelling, MODFLOW is preferred. With MLAEM, there is hardly any experience.

Transparency

The model runs themselves are transparent for none of the models, but there is much documentation about the underlying methods (finite difference, finite elements and analytic elements).

Sub-conclusion

MODFLOW seems to be the most suitable model for policy making. It can simulate compaction and subsidence, uses common input values, can be supplied to all types of soils, is the only model that is suited for local scale problems and has the highest satisfaction. Second best is the groundwater module of SIMGRO. This module can be useful for regional policy making, but has shortcomings on local scale and is user unfriendly. In the future, when these problems are hopefully solved, this module can be an option. MLAEM is the less suited model for end-users, because it needs un-common input data, is very difficult to handle and is unsuitable for solving local scale problems.

Scientific criteria

Models fitting the integration scheme

All models process data in such a way that water heights of surface waters can be transferred to groundwater levels that can serve as input for ecological models.

Temporal issues

All models are dynamic. Due to the features of the groundwater system, temporal scales are very different to those of hydraulic and ecological models for all models.

Spatial issues

All models are spatial. With MODFLOW, spatial resolutions can easily be adapted to those of hydraulic and ecological models. The problem with MLAEM is, that it needs analytical input along rivers that are modelled as line sink elements so interpolation of numerical data is necessary. The spatial scale of SIMGRO can be too coarse to reflect the spatial scale on which most ecological processes and take place.

Compatibility of scientific paradigms

Just like SOBEK-CF and the unsaturated zone module of SIMGRO, MODFLOW and the saturated zone module of SIMGRO assume transient flow. MLAEM, on the other hand, assumes steady flow. Also the analytic approach of MLAEM differs from the numeric approach of SOBEK, SIMGRO and MODFLOW.

Scientifically proven

All models are implemented and scientifically accepted although they are all improved in time, especially SIMGRO.

Sub-conclusion

MODFLOW meets the scientific criteria better then the other two models. Spatial resolutions can easily be adapted to those of hydraulic and ecological models and scientific paradigms are nearly the same of models that should provide its input or handle its output. SIMGRO is second best. The spatial resolution may be too coarse for ecological processes, but scientific paradigms are well-comparable with those of other models. MLAEM can be a very good stand alone model, but the fact that it works in such a different way then other models, makes it unsuitable for integration from a scientific point of view.

Technical criteria

Modularity

The saturated zone module of SIMGRO is easy to extract out of the whole model. Different components of MODFLOW can also be extracted. For MLAEM it is not known whether it is open source or not.

Flexibility

The implementation language of MLAEM is unknown, but SIMGRO and MODFLOW are both programmed in Fortran.

Data

All models can read and produce ASCII files. MODFLOW can also read and produce binary files.

External solver-software

SIMGRO needs external solver software to calculate particle traces.

Compatibility

MODFLOW has an interface with DUFLOW, called MoDuflow, and one with the substance transport program MT3D/RT3D. At this moment SIMGRO has no interfaces with other models, but in the future, interfaces with SOBEK, DUFLOW and MODFLOW will be available. MLAEM has no interfaces with other models and also no developments in this area of interest.

Sub-conclusion

Most of the technical aspects are the same for all models. Only the compatibility with interfaces with other models differs. Especially SIMGRO has an advantage, because in the future, an interface with SOBEK will be available. At the moment, MODFLOW is the only groundwater model with an interface to a surface water model, but no interface with SOBEK is on the stocks. For MLAEM, it is very hard to make interfaces because of the differences in approach between it and most other models.

Organisational criteria

Documentation

SIMGRO has a technical specification, but no specific document at the moment. For MLAEM, a tutorial is available on the internet. There is an extensive publicly available documentation about MODFLOW.

Owner rights

The water boards have owner rights for all models.

Costs

All models are for free (MLAEM only for governmental organisations), but model runs are done external for MODFLOW.

Future developments

At this moment, interfaces between SIMGRO and models like SOBEK, DUFLOW and MODFLOW are developed and in the future it will be possible to make grids where the mash sizes within each grid are not all the same. Future developments of MODFLOW are mainly in the coupling with other models. In the future, MLAEM will give a better representation of the influences of the surficial aquifer and functions to represent a continuously sloping aquifer base. Also, leakage between aquifers is simulated automatically and exactly without the need for specifying area-elements for leakage. Finally, a non-steady version of MLAEM is developed.

Sub-conclusion

MLAEM meets the organisational criteria very well. Both the analytic element method as the model itself are well-documented and many future improvements will be made. Also MODFLOW has many documentation, but is not developed so much any more and is only run by external consultants. Unfortunately, SIMGRO has no specific document, but future developments can make the module an interesting option for integration into an IDSS. Because this development aspect and the fact that MODFLOW is used externally seem more important then the documentation, SIMGRO is ranked above MODFLOW.

Ranking the models

In table J-3, the ranking for the different groundwater models for the saturated zone is given.

Table J-3: Ranking of the groundwater models for the saturated zone

	MLAEM	**MODFLOW**	**SIMGRO**	**Weights**
End-user criteria	0.61	1.00	0.89	0.52
Scientific criteria	0.61	1.00	0.89	0.27
Technical criteria	0.61	0.89	1.00	0.15
Organisational criteria	1.00	0.61	0.89	0.06
	0.633	0.960	0.907	

So, the conclusion can be drawn that MODFLOW is the most suitable for integration into the IDSS. This again does not mean that MODFLOW is automatically integrated. Especially the future possibilities to couple SIMGRO with some other models like SOBEK make it an interesting option when integration of SIMGRO would not be possible. MLAEM can serve well as a stand-alone model, but is not suited for integration into the IDSS, because the approach that is underlying differs to much from that of other models.

Appendix K: Bundesanstalt für Gewässerkunde

The Bundesanstalt für Gewässerkunde (BfG) or German Federal Institute of Hydrology is a higher German authority reporting to the Federal Ministry of Transport, Building and Housing with headquarters in Koblenz and a branch office in Berlin. It is the scientific institute of the Federal Government for research, examination and advice in the fields of hydrology, water management, ecology and water protection and acts as consultant for Federal ministries and their subordinated authorities in general and detailed decision-making. The BfG also advises the authorities of the Federal Waterways and Shipping Administration (WSV) in matters concerning the German waterways from the planning stage, development and new construction, to operation and maintenance. Beyond these tasks, the BfG closely consults with the Federal Ministry for the Environment, Nature Protection and Nuclear Safety, for instance regarding problems of international waters. At its two locations, the BfG has currently about 350 employees, of whom approximately two-thirds work in Koblenz.

In particular, the BfG carries out the following tasks:

- Identifying and solving conflicts of interests between the transportation function of waterways on the one hand and water resources management and ecology on the other hand.
- Developing and practising scientific methods to improve the efficiency of administrative activities.
- Problem-related forecasting in water management and ecological matters.
- Application-oriented consulting.
- Establishing and updating the reference levelling for the German waterways.
- Developing methods for environmental impact studies.

Department U2: Ecological interactions

The internship was carried out at the department U2, that is occupied with the observance of the relations between abiotic and biotic factors in streams and floodplains. It delivers basic knowledge, especially for the ecological oriented questions and fields of activity of the WSV. With the help of mathematical models, ecological effects of measures in the field of hydraulics and water quality are investigated. The department develops precaution strategies and help tools to avoid dangerous situations for the aquatic ecology.

Examples of problems with which the department is occupied:

- Forecasting of the effects of hydraulic and water quality measures on the ecological situation in the German waterways and floodplains.
- Modelling of the dynamics between abiotic and biotic factors in the ecosystem of a floodplain with the help of the integrated floodplain model INFORM.
- Investigation of concentrations and microbiologic communities in streams and floodplains.
- Mathematical simulation of chemical and biologic parameters in the waterways with the help of the deterministic water quality model QSim for water streams and TQSim for tidal waters.
- Characterising of catchment specific plankton communities and analysis of influence factors.
- Assessment of effects of technical products and pollutants on aquatic ecosystems.
- Development of DSS for ecological questions around waterways.

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