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REPORT

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Literature Review on the Open Modelling Interface and Environment (OpenMI)

Project acronym: SAM-CSO

by

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Title

Literature Review on the Open Modelling Interface and Environment (OpenMI)

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Abstract (English)

SAM-CSO – Modeling and impact assessment of combined sewer overflows

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Sub-study: Literature Review on the Open Modelling Interface and Environment (OpenMI)

Within the project SAM-CSO it shall be tested if the Open Modelling Interface and Environment (OpenMI) can be applied to link models of the Berlin sewerage (modelled in the urban drainage software InfoWorks CS,Wallingford Software) to a river water quality model.

This report gives an overview on the OpenMI and its application. *Chapter 1* outlines the general background of integrated water management and integrated modelling as it is aimed at by the European Water Framework Directive. The development process, which resulted in the release of the OpenMI is summarized in *chapter 2*. An introduction to the objectives, the concept and the technology of the OpenMI is given in c*hapter 3*. *Chapter 4* lists case studies in which the OpenMI has been applied. In Appendix B, each of the reported studies has been described in generalized form. A matrix showing all model links, which have been established within the case studies, has been developed. Finally, in *chapter 5*, an overview on other model linking approaches is given.

This report shows that in many use cases the Open Modelling Interface could be used successfully for model linking. Even out of Europe, at a workshop of the U.S. EPA it is stated that, in terms of the ability to go between different temporal and spatial scales, a framework such as OpenMI might have the necessary flexibility. Actually, it was found that in many cases models of the InfoWorks software family have been part of the OpenMI linked systems.

In cases of many interaction points between models, the OpenMI mechanism may not be applicable. In the Berlin case the impact of combined sewer overflows on the water quality of the receiving river shall be examined. With far less than a hundred interaction points between sewer model and river model it is assumed that the OpenMI could be

used for a successful model linking. The difficulty within the SAM-CSO project may be to find an apropriate river quality model, which is ready to be linked to InfoWorks CS using the OpenMI. Unfortunately, there are few use cases reported in which a freely available river water quality model was involved. The water quality model QSIM of the German Institute of Hydrology (BfG) that is used within the project is currently not equipped with OpenMI.

Nevertheless, using the OpenMI mechanism for model linking is assumed to be a promising approach. It is expected to become an internationally accepted standard. As the OpenMI specification is fully free, anyone may contribute to its further development. The OpenMI Association will give advice to modellers and will be open to discussions on improvement of the OpenMI.

With the OpenMI linking mechanism not only models can be linked. Modules for calibration, optimization, statistical evaluation etc. can be part of an OpenMI system as well as components for generic data access or visualization. It will be tested, if the integration of such a module for statistical evaluation into the CSO impact assessment method (to be developed within the project SAM-CSO) is applicable and useful.

Abstract (German)

SAM-CSO – Modellierung und Impakt Bewertung von Mischwasserüberläufen

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Vertragspartner:	Dr. Schumacher Ingenieurbüro für Wasser und Umwelt
Kontakt im KWB:	Kai Schroeder

Teilstudie: Studie über das OpenMI-Framework zur Modellkopplung

Innerhalb des Projektes SAM-CSO soll getestet werden, ob die OpenMI-Schnittstellentechnologie (OpenMI = Open Modelling Interface and Environment) angewendet werden kann, um Schmutzfrachtmodelle der Berliner Kanalisation (modelliert in der Software InfoWorks CS von Wallingford Software) mit einem Gewässergütemodell zu koppeln.

Der Bericht gibt einen Überblick über OpenMI und seine Anwendung. Kapitel 1 führt in die allgemeine Problematik des integrierten Wassermanagements und der integrierten Modellierung, wie sie durch die Europäische Wasserrahmenrichtlinie gefordert werden, ein. Der Entwicklungsprozess, der die OpenMI Schnittstellendefinition hervorgebracht hat, wird in Kapitel 2 zusammengefasst. Eine Einführung in die Ziele, das Konzept und die Technologie von OpenMI gibt Kapitel 3. Kapitel 4 führt Fallstudien auf, in denen OpenMI zur Kopplung von Modellen verwendet wurde. Im Anhang B sind alle Fallstudien jeweils in Form einer einheitlichen Tabelle beschrieben. Es wurde eine Matrix entwickelt, die alle Modellverknüpfungen aufzeigt, die in den verschiedenen Fallstudien realisiert wurden. Schließlich gibt Kapitel 5 einen Überblick über alternative Ansätze zur Modellkopplung.

Der Bericht zeigt, dass die OpenMI Schnittstellentechnologie in vielen Fallstudien erfolgreich zur Modellkopplung eingesetzt werden konnte.

Auch außerhalb von Europa (auf einem Workshop der U.S. Umweltbehörde EPA) wird berichtet, dass OpenMI die nötige Flexibilität aufweist, verschiedene zeitliche und räumliche Skalen in einem integrierten Modell zum Zusammenspiel zu bringen.

In vielen der berichteten Fallstudien waren Modelle der InfoWorks Softwarefamilie Teil des integrierten Modellsystems.

Es wird berichtet, dass der OpenMI Mechanismus im Falle vieler Interaktionspunkte zwischen zwei Modellen möglicherweise nicht anwendbar ist.

Im Rahmen des SAM-CSO Projekts soll die Einwirkung von Mischwasserüberläufen auf die Wasserqualität der aufnehmenden Gewässer untersucht werden. Mit weit weniger als hundert Verknüpfungspunkten zwischen Kanalnetzmodell und Gewässermodell ist zu vermuten, dass OpenMI erfolgreich für die Modellkopplung eingesetzt werden kann.

Die Schwierigkeit könnte sein, ein für die Kopplung passendes Flussgütemodell zu finden. Leider wurde in wenigen der berichteten Fallstudien ein Flussgütemodell verwendet, das als freie Software verfügbar ist. Das Gewässergütemodell QSIM der Bundesanstalt für Gewässerkunde, das im Rahmen des Projekts verwendet wird, ist zur Zeit nicht mit OpenMI ausgestattet.

Der OpenMI Mechanismus wird als vielversprechender Ansatz betrachtet. Es ist zu erwarten, dass er ein international anerkannter Standard wird. Da die OpenMI-Schnittstellenspezifikation frei verfügbar ist, kann jedermann zu seiner Weiterentwicklung beitragen. Seitens der *OpenMI Association* ist Unterstützung bei der Anwendung von OpenMI sowie Offenheit gegenüber Vorschlägen zur Verbesserung und Weiterentwicklung der OpenMI Schnittstellendefinition zu erwarten.

Mit dem OpenMI Mechanismus können nicht nur Modelle untereinander gekoppelt werden. Auch Module für automatische Kalibrierung, Optimierung, statistische Auswertung usw. können Teil eines OpenMI Systems sein, sowie Komponenten für vereinheitlichten Zugriff auf Datenquellen oder für die Datenvisualisierung. Im Rahmen des SAM-CSO Projekts soll getestet werden, ob die Verwendung eines solchen Moduls für die statistische Auswertung von Simulationsergebnissen geeignet und hilfreich ist.

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Chapter 1
Introduction

In the past, 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 mostly in isolation. The effects of any given decision were usually local [2]. Now, this is no longer the case. An apparently beneficial decision in one area of policy or operation can have major and often less desirable repercussions elsewhere, in both the natural and man-made environments [2]. So, managing environmental processes independently does not always produce sensible decisions when the wider view is taken [3]. In the water domain, the European *Water Framework Directive* (WFD) takes this into account and calls for *integrated water management* to be put into practice.

The aim of integrated water management is to develop and implement sustainable policies that reconcile the competing demands for the use of environmental resources within a catchment [2, 4]. Catchments should be considered as a whole, not being devided at political borders. Implementing integrated catchment management 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 [2].

Indeed, the processes to be managed are so complex and require such a breadth of understanding that integrated catchment management is beyond the capacity of most normal people to deliver [3]. Therefore, *decision support systems* (DSS) assist managers in their decision making process [2].

DSS are comprised by models which are used to predict the likely outcomes of different options for given scenarios [2, 4]. In this context, the WFD identifies the *integral modelling* of whole catchments as a key mechanism of the integrated approach to environmental management [5, 6]. The objective of integrated modelling is to provide the catchment manager with a better understanding and prediction of consequences of following any given policy or programme. For example, it should be possible to model the socio-economic implications of river regulation. [2, 3, 7] The challenge that integrated modelling presents is not only that individual catchment processes but also their interactions have to be understood and able to be modelled and simulated [3, 6]. The complexity of environmental processes and interactions between processes make this a difficult task [2, 4].

Up to now, processes have been widely considered in isolation. Consequently, there have been developed specialized models, which were able to address single specific issues. Now, as it is required to investigate the interactions between the different systems the corresponding models have to interact in an adequate manner. It is not a feasible option to construct a new single model of all the processes taking place within a catchment [2]. Different situations require different combinations of models [2]. A single model would not make good use of existing models and it would not provide the flexibility to try alternative models for individual processes [6]. The better approach is to link existing models. The reality for many years to come is that model linking will be used to simulate complex processes [2].

The traditional way of model integration is to model different systems, e.g. sewers and rivers, separately, with different models being implemented in different software applications. The model applications are run one after the other, with the outputs from one model run being input into the other model. With these separated model runs interactions between the models are not taken into account. An example for model interactions is the influence of sewerage discharge to the level of the receiving watercourse which can have subsequent effects on the sewerage system. [5]

Until few years ago, few current models were designed for linking and there was no generic operational linking mechanism like a plug and play mechanism that allowed models of large multi-national catchments or complex processes spanning many disciplines to be built up [2, 4]. Model linking was therefore either confined to the products of a single supplier or required a major software development exercise [2].

However, technological advances in computing made it possible to develop such model linking mechanisms. In 2002, an environment for model linking was released as a result of the European project *HarmonIT* within the Fifth Framework Programme. The mechanism which is called *Open Modelling Interface and Environment* (OpenMI) is subject of this document. The OpenMI defines a standard interface that allows time-dependent models to exchange data at run-time. A linkage mechanism, such as the OpenMI, is the key to moving single domain modelling to integrated modelling by making model integration not only a research exercise but feasible at the operational level. It will allow for integrated water management to be put into effect and, hence, the objectives of the WFD to be achieved. [6]

This paper first descibes the development process of the OpenMI and how this model linking standard will be maintained and further developed in the future (*chapter 2*). In *chapter 3*, an introduction to the OpenMI is given, containing the objectives and a description of the general concept and the linking mechanism. *Chapter 4* summarizes the results of an internet and literature review that aimed to look for documented case studies in which OpenMI was applied in practice. *Chapter 5* gives an overview about other frameworks for model integration. Finally, in *chapter 6* the results of this review are summarized and conclusions are formulated.

Chapter 2
The Development Process

The Open Modelling Interface and Environment (OpenMI) is the product of the EU project HarmonIT (see 2.1). Its application and maintenance is promoted by the EU project OpenMI-LIFE (see 2.2). In order to achieve the aims of the latter, the OpenMI Association has been founded (see 2.3).

2.1 The EU-Project IT Frameworks – HarmonIT

The first version of the Open Modelling Interface and Environment (OpenMI) is the result of the research project “HarmonIT” which was funded and supported by the European Commission’s Fifth Framework Programme (FFP) under contract number EVK1-CT-2002-00090 [6]. The project was contributing to the implementation of the Key Action “Sustainable Management and Quality of Water” within the sub-programme “Energy, Environment and Sustainable Development”. The HarmonIT project is one of a cluster concerned with developing the methodologies and tools required to implement integrated water management as envisaged by the Water Framework Directive [4]. The runtime of the HarmonIT project was from 2002 to 2005 (4 years).

The objectives of the project were to identify the user requirement for model linking and to develop, implement and prove a standard Interface and Environment that will simplify the linking of models, especially those related to hydrology, and address all the problems involved. In order to enhance user acceptance for the standard, one of the primary design objectives of the OpenMI was to facilitate the migration of existing models to the new standard so that they are more widely accessible [3]. Allowing to explore the likely outcomes of different policies, the establishment of the OpenMI should support and assist the strategic planning and integrated catchment management required by the Water Framework Directive. [2, 3]

The OpenMI was developed by a team drawn from 14 organizations and seven countries (see Appendix A, HarmonIT-Participants). Led by the Centre for Ecology and Hydrology in Wallingford, UK, the development has primarily been undertaken by the three major commercial model developers, DHI Water and Environment (Denmark), Delft Hydraulics (Netherlands) and HR Wallingford (UK). The role of the other organizations has been to manage the project, to support the design and development and to test the standard and environment [6].

Based on a review of use cases representing the current practice and on a requirements analysis, an architecture was chosen. The architectural design has been extended into a clear, well-documented and detailed specification document, covering the so called framework of the OpenMI, including data models, data definitions, linkage mechanisms, and interface definitions. Tools for creating and monitoring model links and for managing the linked models have been specified and designed in detail. Framework and tools have then been implemented into an operational software code. To test the implemantation, a selection of available existing simulation models used in water management have been migrated to the IT framework. The project has been documented in forms of guidelines. Finally, all files comprising the OpenMI and the documentation have been made available to the modelling community.

To ensure that the work met the standards required by the Commission and the scientific and user communities, a panel of experts has reviewed the key documents and advised the Steering Committee. The project's quality assurance plan established procedures for the critical areas of work and covered document and code version control. [6]

2.2 The OpenMI-LIFE Project and other Projects

To turn the OpenMI from research outcome into a sustained standard for operational practice, a second project has been initiated under the policy area "Sustainable management of groundwater and surface water management" of the European Commission's LIFE Environment programme (Contract no : LIFE06 ENV/UK/000409). The OpenMI-LIFE project began in October 2006 and runs until January 2009 [8]. Led by the Centre for Ecology and Hydrology (UK), the team comprises 12 companies from five european countries (see Appendix A, OpenMI-LIFE-Participants).

The objective of the OpenMI-LIFE project is to setup a structure for technical support, maintenance and dissemination of the OpenMI and to provide all relevant information to the users. The OpenMI Association has been founded to coordinate these activities (see 2.3). The technical work concerning the maintenance and the improvement of the OpenMI is being conducted by nearly the same team in a similar way as in the HarmonIT project [6].

In order to demonstrate that the OpenMI is a useful tool for model integration and that it can help achieving the objectives of the Water Framework Directive the project supports two case studies in which the OpenMI will be applied in real-life situations. The case study areas are the Scheldt basin in Belgium and the Pinios basin in Greece (see 4.3) [9].

OpenMI is being used by various other projects, both EU funded and national funded. However, it is reported that so far, few projects provided feedback to improve the OpenMI technology although the OpenMI-LIFE project welcomes all kinds of contribution [6].

2.3 The OpenMI Association

Adopting the OpenMI requires model developers to make a commitment which most organizations cannot afford until the OpenMI is widely available in a number of implementations and is properly supported – in other words: until it has become a well-maintained standard [6]. To support and maintain the OpenMI, and to stimulate the development and increase the wider use in practice, an association has been established under Dutch law: The *OpenMI Association*.

The association is a membership based organization that manages the future maintenance and development of the OpenMI as a worldwide-applied software standard for model linkage in the water and other environmental domains. It supports the user community by disseminating information and promoting knowledge exchange and further development of the OpenMI via the Internet. More information on the OpenMI Association, and its membership, is available at its website: `http://www.openmi.org`. [6]

Chapter 3
Overview of the Open Modelling Interface and Environment (OpenMI)

The Open Modelling Interface and Environment (OpenMI) defines a standardized way to exchange data between environmentally related, computational models that run simultaneously. OpenMI aims to enhance the representation of process interaction in integrated environmental modelling. Integrated modelling is seen as a key tool for an integrated water management as aimed by the European Water Framework Directive. The OpenMI is developed as an open source project hosted at the internet plattform SourceForge.net (see `http://sourceforge.net/projects/openmi`). Currently, there are 24 registered developers participating in the project. The current version of the OpenMI is 1.4.0.0 from December 2007. Documentation about the OpenMI is provided in terms of the *OpenMI Document Series,* available for download at `http://public.deltares.nl/display/OPENMI/OpenMI+documentation+index`.

3.1 Objectives and Challenges

General objectives of the OpenMI are to provide a generic model linking mechanism which:

- enables the modelling of entire catchments including the interactions of relevant processes within the catchments,
- enables the coupling of existing models representing different subcatchments or different interacting processes,
- enables the communication (data exchange) between models representing different domains (e.g. hydrology, water quality, ecology, economy) and based on different concepts (e. g. deterministic, stochastic),
- allows to model the interactions of environmental processes realisticly,
- is easily applicable, especially to existing computer models (so called legacy code),
- does not only support the linking of models between each other but also the linking of models with data sources like databases or user interfaces, as well as with other simulation tools like programs for data monitoring, calibration or optimization.

The OpenMI standard has to meet some of the following challenges:

- Models of different spatial domains (one, two, three dimensional, network, grid, polygon) and temporal domains (hourly, daily, monthly, etc.) shall become linkable. Unit conversion between variables should be supported.
- For a more realistic representation of model interactions an alternative to the traditional way of (pseudo-) integrated simulation (according to which models are run one after the other, with the results of the first model being input into the second model) has to be found. Therefore, it must be possible to exchange data at model runtime, at every time step of the simulation of the system of linked models. Model interactions must not be limited to a unidirectional data exchange from one model to a second model but feedback of the second model back to the first model must be possible.
- In order to make legacy code reusable, cost, skill and time required to migrate an existing model to the standard should not prevent from using the standard. It shall be possible for water managers and decision takers without a deep knowledge in programming to set up a system of linked models.
- The standard should be independent from computer architectures, operating systems and programming languages.

3.2 Terminology

As shown in Figure 1, a *model application* software usually consists of a *user interface* and an *engine*.

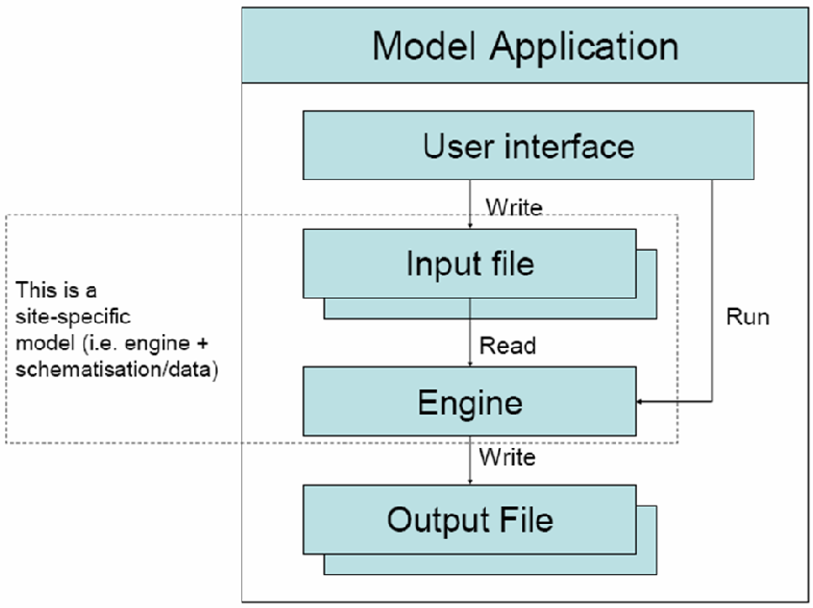

Figure 1: Usual structure of a model application

Usually, the *engine* represents the modelled processes. It does the calculations needed to simulate these processes. By means of the *user interface*, the user specifies input data which describe a specific scenario in which the processes take place (also called the model *schematization*). The input data is stored in an *input file*. If the engine gets populated with site specific data, which it reads from the input file, it becomes a *model*. That model can then be run by activation through the user interface. It performs the necessary calculations and writes the results of the simulation to an *output file*.

The strict separation of input, processing, and output is a precondition for making existing modelling softwares compliant to the OpenMI standard.

3.3 Concept of the OpenMI

In the architecture of a model application (Figure 1) the model is accessed through the user interface. Generally, the communication between user interface and engine can be different in different software applications. User interface and engine communicate by means of calls of procedures (also named functions or methods) within the model application software. Thus, the communication depends on the software technology (e.g. the programming language) in which the software application is realized.

The idea of the OpenMI linking mechanism is to make model engines generically accessible from outside the model applications in which they are normally applied. Therefore,

1. a convention for the data exchange between engines must be found,
2. it must be possible for an engine to exist autonomously, without the need of being hosted by a surrounding model application.

To meet the *first* requirement, the OpenMI specification defines a set of conventions (predefined methods with predefined parameter lists) for the data exchange between different engines. This specification, which is meant by the OpenMI *Interface*, can be seen as a common “language” between the engines. Every engine which “speaks” the language can communicate (exchange data) with every other engine speaking the same languague. The process of “teaching” engines to speak the Open Modelling Interface “language” is called the *implementation* of the OpenMI interface.

An engine which can act as an independent object and so meets the *second* requirement, is called an engine *component*. Components which, furthermore, have implemented the OpenMI interface (i.e. offer access methods as defined in the OpenMI interface specification) are called *OpenMI-compliant* model components. They are also refered to as *Linkable Components* [10, p. 9].

After giving some additional information on the OpenMI standard interface (see 3.3.1), it is explained, how data is exchanged in a linked system of OpenMI-compliant components at runtime (see 3.3.2).

3.3.1 The OpenMI standard interface

The OpenMI standard interface defines the methods every Linkable Component must offer in order to allow it to become part of an OpenMI linked model system. These methods can be divided into three groups [6]:

- Model definition: To allow other linkable components to find out what items this model can exchange in terms of quantities simulated and the locations at which the quantities are simulated.
- Configuration: To define what will be exchanged when two models have been linked for a specific purpose.
- Run-time operation: To enable the model to accept or provide data at run time.

Concerning run-time operation, the key access method which is defined in the interface specification is the *GetValues* method. This method is used at model runtime to request the value of a model variable at a specific point in space and time.

Figure 2 shows two model applications whose engines have been made OpenMI-compliant. Their overall structure remains the same but each engine is now a component with an OpenMI interface enabling each component to get values from the other. [6]

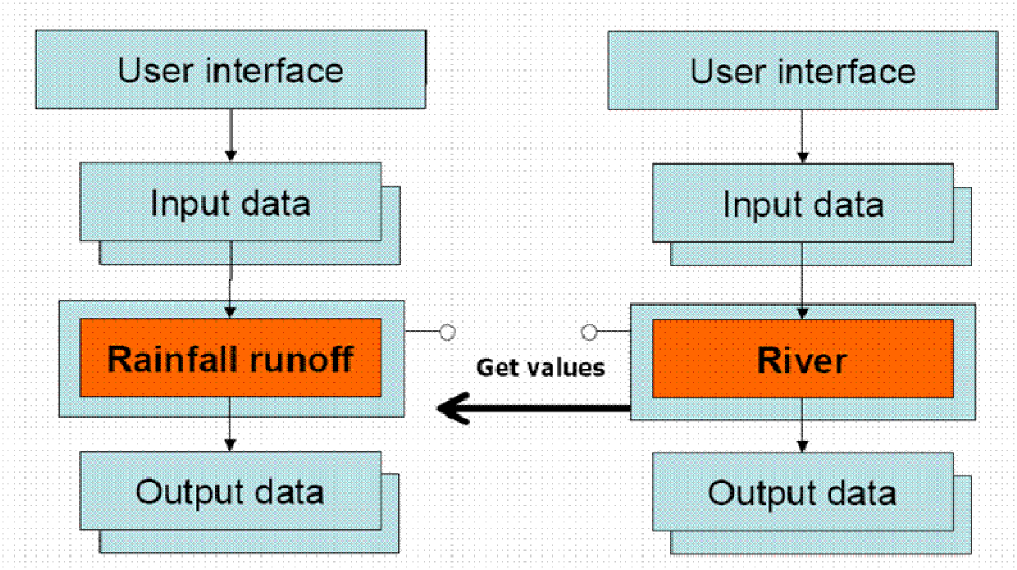

Figure 2: Two applications after migration to the OpenMI standard (taken from [6])

Before models can be run together, *links* between particular pairs of models have to be created. A link defines which quantity will be exchanged across the link, in which direction, and between which locations. Human involvement is needed when the links are being specified. To facilitate the linking process, every linkable component publishes the input and output variables as well as the geographical locations at which values of the quantities are available in the model.

In order to bring models of different spatial domains together, the model components have to implement methods for spatial mapping. Figure 3 shows the geographical matching of elements in a river model to those in a groundwater model. The river model is a vector model and each element represents a single stretch; the groundwater model is grid-based, each node being an element. Therefore, in order to link the two models, each element in the river model will usually be linked to several elements in the groundwater model. In any non-trivial situation, this will require the matching of thousands of elements and therefore the process is automated [6]. Data operations which have to be performed to realize the mapping of corresponding locations are part of the link definition and have to be implemented by the component.

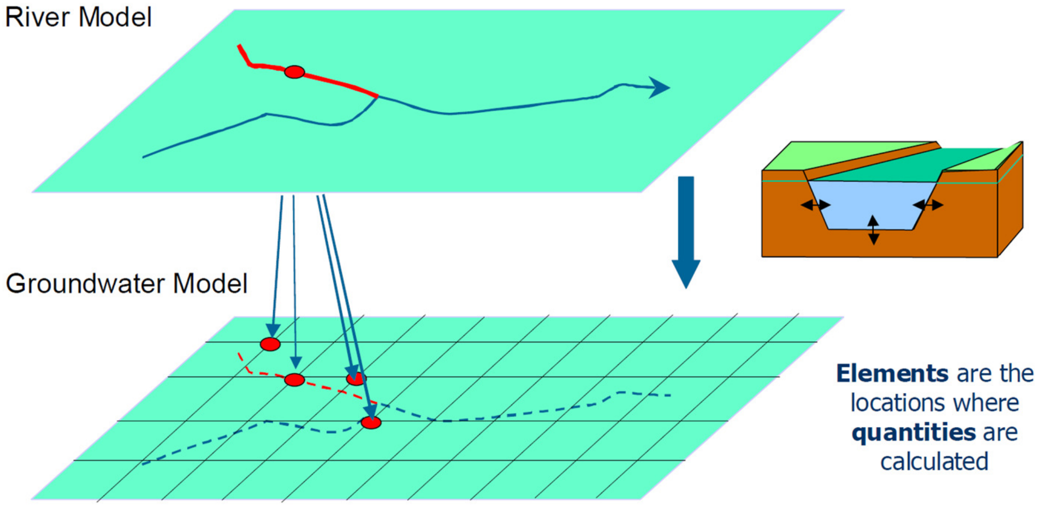

Figure 3: Spatial mapping (taken from [6])

In order to link models of different temporal domains, every linkable components must be able to provide a demanded value for any requested point in time. Therefore, it may be necessary to implement the GetValues method in such form that it performs a temporal mapping before returning a value. This may include the interpolation, extrapolation or aggregation of the simulated timeseries of a quantity [10, p. 23].

Data exchange along a link is only in one direction, namely from the data provider to the data acceptor. However, bi-directional data exchange for modelling feedback between models can be achieved by means of two contrarily directed links. Data transfer is not realized by means of files but takes place directly in the (random access) memory of the computer.

3.3.2 The Request-Reply-Mechanism for Data Exchange

Unlike other approaches in model linking, OpenMI is not an environment (a software application) which contains predefined model components and which controls the linking and running of these components within that environment. Rather, an OpenMI linked system consists of standardized individual OpenMI-compliant components which can be linked using an appropriate general technology for component communication (see 3.4).

There is no need for a controller component to control the flow of data between the different model components. The data exchange and synchronization mechanism is designed in such way that linkable components can autonomously exchange data without any centralized functionality to manage the data exchange [10, p. 29].

In an OpenMI-linked system, components communicate by acting as *data providers* and/or *data acceptors*. For data exchange, a so called *Request and Reply mechanism* (or "Pull-Mechanism") is used: If a model component needs for its calculation a value of a quantity which another component is responsible for, it requests that value from the data providing component. That data providing component calculates the desired value and returns it to the demanding component. If the providing model, in turn, needs data from another component, it becomes a data acceptor, requesting data from that other component and waiting until it provided the desired data. A data accepting component does not continue with its calculations until the corresponding data providing component calculated and delivered the desired value. So, a component always handles only one request at a time before acting upon another request. A so called trigger component is needed to define the beginning of the exchange chain [10, p. 9].

Figure 4 shows two examples in which model components are linked. In the lefthand example, data exchange between each pair of linked models is one-directional. By contrast, the righthand example shows a bi-directional data exchange between model components B and C.

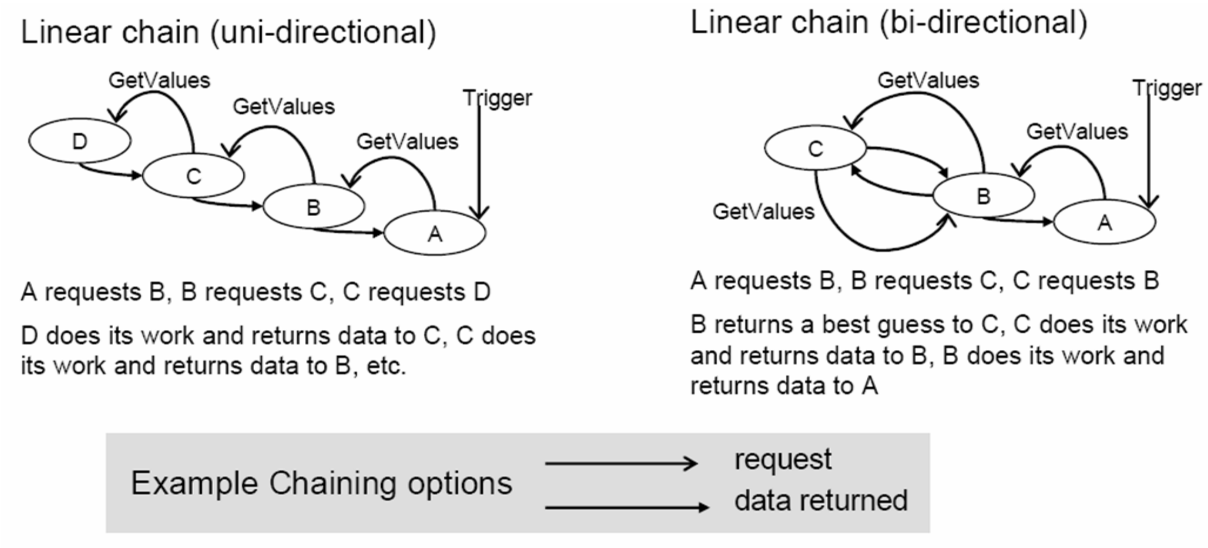

Figure 4: Linking of model components (taken from [11])

Component A on the left could be a model representing water quality in an estuary. That model gets triggered and begins calculation. Model A depends on input from model B, which could be a river quality model. By calling the GetValues method of B, A could for example request contaminant concentrations at the end of the river stretch. Before river model B could provide the demanded data, it would, in turn, need the results of another model C (e.g. groundwater, rainfall runoff or sewage model) for its calculation. Finally, model C could be dependent on the results of a last model D. The total flow of data results from the sequence of requests which the model components send to each other.

3.4 Software Technology

Stictly speaking, OpenMI is only an interface specification, defining methods which model components to be coupled must implement to make them OpenMI-compliant. The specification itself is independent from any specific software technology and does not limit the implementation to a specific programming language or computer environment. The model developer and model integrator are responsible for chosing a software technique which enables the communication of different software components technically. While the interface specification defines *which* methods must be offered by a model component to be OpenMI-compliant, the software technology determines *how* these methods can be called and how data is transmitted between the components.

The *Microsoft .Net Framework* is such a technique which enables communication between software components. In order to support the process of making existing models OpenMI-compliant, the OpenMI interface specification can be downloaded in terms of source code written in the programming languages C Sharp (C#) or Java. In the current version OpenMI 1.4, the SDK is only available as .Net version, but it is planned to be distributed as Java code as well. Using these prepared interface definitions makes it easy to implement the OpenMI interface in the according programming languages and to build software components which can communicate within the .Net environment. The programming language C# is one of the languages supported by the .Net Framework. So, an OpenMI-compliant model component, being developed in C# can communicate with other model components, being developed in any of the languages supported by the .Net framework.

3.5 Working with the OpenMI

OpenMI systems are software systems that combine a set of OpenMI compliant components (see 3.3). In order to build an OpenMI system, first the models which are intended to be linked have to be provided in the form of OpenMI compliant components. Existing models which are not already OpenMI compliant have to be adapted to the OpenMI standard by *Model Migration* (see 3.5.1). Then, if all components are available, an OpenMI system can be set up (see 3.5.2).

3.5.1 Model Migration

In order to migrate existing models (legacy code) to the OpenMI standard, the original engine needs to be turned into an engine component and the engine component needs to implement the OpenMI interface. The engine component then becomes an OpenMI-compliant linkable component that becomes accessible to other components providing direct access to their data at run-time [11].

To become an OpenMI linkable component, an existing model engine must at least satisfy the following criteria:

- structural separation of initialization and computation,
- ability to expose information on the modelled quantities,
- knowledge about current time and ability to provide (if necessary inter-/extrapolated) values of available quantities for any point in time and space,
- ablility to respond to a request by an outside entity.

The migration of engines satisfying these criteria into linkable components can be done in terms of a process called *wrapping*. In doing so, the program code of the engine is embeded in a prepared software shell which already complies the OpenMI standard. The OpenMI Software Development Kit (see 3.6) provides such a wrapper that already handles most of the tedious (and difficult) tasks to be performed. The component developer has to care about the correct internal linking of the method calls (coming through the standardized interface) with the corresponding calls in the original program code. In [11] the model migration is explained as a seven step process.

3.5.2 Developing OpenMI systems

OpenMI systems need to

- know which components they comprise and where to find these components,
- know what links exist between the components,
- be able to instantiate, link, deploy and run the components.

OpenMI systems can come in two types:

- hard-coded systems,
- configurable systems.

In *hard-coded systems* the establishment of the links and the deployment and execution of the components is fully encapsulated in the source code. An example of developing a hard-coded system by means of an eight steps procedure can be found in [11].

In contrast, c*onfigurable systems,* allow to inspect components for the exchange items they offer and provide facilities to link the compontents (i.e. by drag and drop) using a graphical user interface (GUI). The configuration of the system (also refered to as a composition) can then be saved in forms of an XML (Extensible Markup Language) file. The main aspects of a configurable system, with some details of the tools provided in the OpenMI Software Development Kit (SDK, see 3.6) are discussed in [11]. The OpenMI is shipped with such a graphical user interface, namely the OpenMI Configuration Editor.

Six phases for establishing and running a combination of OpenMI linkable components can be distinguished:

1. *Instantiation & Initialization*: The application first reads information about the linkable components (which is stored in so called OMI-files in XML format) and constructs the components (instantiation) and then may populate the components with input data (initialization).
2. *Inspection & Configuration*: In configurable systems, components are inspected for available input and output exchange items. Links can be added and components and links can be validated.
3. *Preparation*. This phase which comes just before computation should define a clear take-off position. Model engines may be populated with data, files may be opened or database connections established, buffers may be organized etc.

4. *Computation/Execution*: The models are run applying the request reply mechanism for data transfer.
5. *Completion*: Files and network connections are closed.
6. *Disposal*: Objects are cleaned and memory is de-allocated.

3.6 The OpenMI Software Development Kit (SDK)

The OpenMI specification is delivered with a software development kit (SDK) which supports the model developer in the migration of existing models into OpenMI-compliant components as well as in setting up and running linked models. The SDK provides additional utilities (see [10]). The SDK contains:

1. *Buffer* which holds calculated values and offers methods for delivering these values or values between timestamps (interpolation) or values out of already calculated timespans (extrapolation). So, values at any timestamps requested by linked models, can be delivered.
2. *Spatial package* for mapping between zero dimensional (point), one dimensional (polylines) and two dimensional (polygons) data. The spacial package does not contain very advanced methods but provides the model developer with functionality (in terms of class definitions) which can easily be extended.
3. *Wrapper,* see 3.5.1
4. Package *AdvancedControl which* provides classes that help the model developer to implement additional control for the data exchange. Additional control is needed to direct convergence of computational results. This functionality is typically desired for iteration purposes, as well as for optimization and calibration. The controllers themselves are linkable components, so their data (i.e. new parameter values or boundary conditions) can be accessed by a linkable component as well. Accordingly, an iteration controller, an optimization controller and a calibration controller are provided by the SDK (see [10]).
5. *Configuration* package which contains methods to save, retrieve and deploy a setup of linked models, determining the involved model components and their links.

Chapter 4
Application of the Open Modelling Interface

4.1 General

The OpenMI cannot be applied only in the water domain but in many more fields. However, its base will remain the environmental domain where temporal and spatial variability are key issues in understanding and managing systems. The founders of the OpenMI believe that they have created a software architecture that has a big potential to become a global standard for model linkage and data exchange in the environmental domain. Evidence for this view can be found in the number of projects within the Sixth EU Framework Programme (FP6) that use the OpenMI. Universities, software developers and competent authorities in Europe and the U.S. are interested in, intend to use or already use the OpenMI [6].

A number of communities in the U.S. have been expressing interest in the OpenMI. In April 2008, the U.S. National Science Foundation (US-NSF) funded seven U.S. scientists of the Consortium of (120) Universties for Advancement of Hydrologic Science (CUAHSI), to attend an OpenMI workshop. One of the aims was to identify shared interests and to initiate collaboration. In 2009, there will be the first public OpenMI training course and a workshop on integrated modelling in the United States. CUAHSI will join the OpenMI Association (see 2.3) and take an active part in the OpenMI's future development [12]. The United States' Environmental Protection Agency (EPA) hosted a workshop on OpenMI in January 2007 (Workshop title: "Integrated Modeling for Integrated Environmental Decision Making") [1]. These examples show that the application of the OpenMI is not limited to European countries although it is the result of a European project (HarmonIT, see 2.1) [5].

In the following, case studies are presented, in which the OpenMI was or will be applied. They are reported by the OpenMI Association or by model users and developers. Starting point for the search for case studies was the Homepage of the OpenMI Association (`http://www.openmi.org`). Currently, the OpenMI Association (see 2.3) lists six individual case studies (see 4.2) and two projects including case studies. One project is the OpenMI-LIFE project (see 2.2) which supports "use cases" related to the Scheldt water basin in Belgium (see 4.3.1) and to the Pinios basin in Greece (see 4.3.2). The second reported project is the OpenWEB project by Wallingford (see 4.4).

Apart from the OpenMI-LIFE case studies, the OpenMI-"Wiki" (`http://public.deltares.nl/display/OPENMI`) lists further "Use Cases". They can (hardly) be found following the path "OpenMI Association Technical Committee > OATC Development >

OpenMI version 2 development > Use Cases". Some of them seem to represent a discussion on desired additional functionality of the OpenMI. As the additional reported use cases are mainly poorly described, these examples are not considered here.

A further literature and internet review revealed three further case studies. Here, these will be reported last (see 4.5).

In order to facilitate their comparison, all case studies have been described in terms of a generalized form (see Appendix B). The form lists information on the project responsibles, objectives of the study, and the involved models as well as the actions which have been undertaken within the study and the achieved results and conclusions.

An overview of all of the model links which have been realized in the considered case studies is given in 4.6.

4.2 Individual Case Studies reported at www.openmi.org

The homepage of the OpenMI Association (`http://www.openmi.org`) lists six individual case studies in which the OpenMI was applied. In four of them the Software InfoWorks CS for sewer simulations was coupled with the river modelling software InfoWorks RS. Both softwares are developed by Wallingford Software. In three of these case studies catchments in the UK were investigated, the fourth study took place in Japan. A fifth case study deals with an OpenMI-compliant component which acts as a data provider, allowing other OpenMI components to access stored data in a generic way. About the sixth reported case study "Surface-Groundwater Interactions Using the OpenMI" no additional information could be found. See Appendix B.1 for the formal description of all of these case studies (named C1 through C6).

4.3 Case Studies within the OpenMI-LIFE Project [13]

The OpenMI-LIFE project (see 2.2) demonstrates the use of the OpenMI to facilitate model linking in the Scheldt (Belgium, Netherlands) and Pinios (Greece) pilot river basins. Those basins face different water resources issues whose management demands an integrated approach. The Competent Authorities identified the current status and specific pressures related to those issues. The Modelling Community decided to use models linked in the OpenMI to perform an integrated analysis and indicate the likely outcomes of different policies to the Competent Authorities. Selected model developers upgraded their relevant models to become OpenMI-compliant. During the whole project, the OpenMI Association guides, maintains and supports the integrated modelling effort in response to developer and user requests.

Information about the OpenMI-LIFE use cases can be taken from presentations and promotional material which can be downloaded from the OpenMI-LIFE website (`http://www.openmi-life.org`). Additional documents about the studies could be found on the internet.

4.3.1 Demonstration Case Studies in the Scheldt Basin within OpenMI-LIFE [14-17].

Project coordinator of the case studies in the Scheldt basin is the Flemish Environment Agency (VMM), Belgium [17].

The Scheldt (Dutch: Schelde, French: Escaut) is a 350 km long river. It takes mainly its sources in northern France and flows through western Belgium to finally enter the southwestern part of the Netherlands before ending in the North sea [18].

Concerning the basin of the river Scheldt, four use cases have been defined:

ID	Use Case	Topic	Models involved
S1	Scheldt Use Case A	Impact of sewer discharges on a river during flooding	InfoWorks CS, InfoWorks RS
S2	Scheldt Use Case B	Influence of river flow regulations on flood risk in a river	InfoWorks RS, MIKE-11
S3	Scheldt Use Case C	Effect of flow regulations on water quality	InfoWorks RS, MIKE-11, PEGASE
S4	Scheldt Use Case D	Influence of tides on upstream flood risk	MIKE-11, Waqua, Delft3D

According to [19], the objectives of the case studies in the Scheldt were to:

- demonstrate the applicability and the added value of OpenMI in linking models (e.g. two river models) which have been developed independently and with different modelling softwares,
- demonstrate how physical (two-way) system interactions can be dealt with by linking models (of different extent and detail) at runtime,
- make the required models OpenMI-compliant (if not already done) and to modify them conceptually in order to make them linkable,
- realize system interactions first with the OpenMI compliant models being run independently in each software system (unlinked) and then within an OpenMI linked system. The output of stand-alone and linked model runs shall be compared in order to assess the quality of the results calculated by the linked models.

See Appendix B.2 for a formal description of the Scheldt use cases (named S1 through S4).

4.3.2 Demonstration Case Studies in the Pinios Basin within OpenMI-LIFE [14, 15].

Project coordinator of the case studies in the Pinios Basin is the National Technical University of Athens (NTUA), Greece [17].

The sustainability of the Thessaly area depends greatly on quantity and quality of water in the Pinios [19]. The Pinios river flows from the Pindus mountains and empties into the Aegean Sea. It creates a large delta, well-known for many animal species and protected by international environmental treaties. The total length is 216 km and it begins in the north at the Pindus ranges east of Metsovo. The Meteora region and the cities of Trikala and Larissa lie along the Pineiós [20]. The whole Pinios basin (including Lake Karla) drains an area of approximately 10,500 km2. Eight significant tributaries contribute their flows to the main channel [21].

The interrelated water quantity and quality concerns of the Pinios basin demand an integrated modelling approach. Irrigation has led to decreased ground water levels and river flows. Water quality is influenced by fertilizers, pesticides, industrial and municipal wastewater. [21]

Concerning the basin of the river Pinios, three use cases have been defined:

ID	Use Case	Topic	Models involved
P1	Pinios Use Case A:	Effect of advection-dispersion on sewage effluent discharge	MIKE-11, RISH-1D, R-Qual
P2	Pinios Use Case B:	Impact of climate change scenarios on a reservoir	MIKE-11, RMM-NTUA
P3	Pinios Use Case C:	Lake basin restauration	UTHBAL, Visual Modflow

All three scenarios use the OpenMI technology to facilitate the integration of in-house developed models with suitable models of other developers in order to successfully represent the different processes that interact in the basin. The three case studies focus on different water management issues. [19]. See Appendix B.3 for a formal description of the Pinios use cases (named P1 through P3).

4.4 Case Study OpenWEB project [22]

A major focus for HR Wallingford in 2008 is the development of the OpenWEB software platform to stimulate the evolution of integrated modelling solutions. The project brings together academic and industrial partners to create collaboratively the next generation of integrated water environment models. The OpenWEB platform, built using the OpenMI standard, will feature facilities such as an evolving toolbox (that includes common data sets) and model validation cases (to facilitate the testing of newly developed model compositions).

4.5 Further Miscellaneous Case Studies

Apart from the above mentioned case studies which were officially reported by the OpenMI Association (see 2.3), only three further documented case studies could be found. See Appendix B.4 for a formal description of these use cases (named M1 through M3). Out of the studies, only study "M1" was undertaken by an organization which did not participate in the HarmonIT project.

4.6 Overview of linked models

Figure 5 shows an overview of the OpenMI-compliant models which have been used within the reported case studies and the established links between these models in terms of a matrix.

In the figure, the acronyms at the crossing points (C1…C5, S1…S4, P1…P3, M1…M3, as introduced in 4.2 through 4.5) represent the case studies, in which the corresponding models have been linked in the given direction. Example: Case study S4 used a bidirectional link between Delft3D and MIKE-11 (see "S4" at crossing of row "Delft3D" and column "MIKE-11" as well as at crossing of row "MIKE-11" and column "Delft3D") whereas in case study M3 a unidirectional link from STOAT to SULIS (see "M3" at crossing of row "STOAT" and column "SULIS" but "empty" crossing of row "SULIS" and column "STOAT") was established. The upper part of the figure indicates the domains (Rainfall runoff, Sewer, River, Groundwater, Other) and parameters (flow, quality) which are represented by the models.

In most of the cases the modelling systems InfoWorks CS and InfoWorks RS by Wallingford Software have been coupled (in both directions). Only in one case InfoWorks CS was linked to another model software (STOAT in case study M3), whereas InfoWorks RS got input data also from some other models (MIKE-11, PEGASE, SOBEK-River 1DFLOW, and SULIS). Actually, InfoWorks CS, InfoWorks RS and MIKE-11 are the only model softwares of which the usage is reported in more than one case study. Apparently, this is due to the fact, that in many of the case studies models have been used which are in-house developments of the participating project partners (e. g. GEIWrapper by the German Federal Waterways Engineering and Research Institute or the products RiSH-1D, RMM-NTUA and R-Qual which have been developed at the Centre of Hydrologic Information (CHI) of the National Technical University of Athens (NTUA)).

In many cases, only one-directional links have been established; so some models only acted as data senders (GEIWrapper, HYMOS, SMUSI, SOBEK-Urban 1DFLOW, UTHBAL), others only as data receivers (ArcGIS, BlueM, RMM-NTUA, UnTRIM, Visual Modflow).

Type of Receiving Model v v																									
Other	x	x	x			x	x							x						x	x	x			x
Rainfall runoff				x				x	x	x						x		x					x		
Sewer								x								x			x						
River				x	x				x	x		x	x		x		x								
Groundwater											x												x	x	
Water Flow				x	x			x	x	x		x	x				x		x		x	x	x	x	x
Water Quality				x	x			x	x	x		x			x						x	x		x	x
Receiving Model >>	Agricom	AM-DSS	ArcGIS	BlueM	Delft3D	GEIWrapper	HYMOS	Info Works CS	Info Works RS	MIKE 11	Mozart	PEGASE	RiSH-1D	RMM - NTUA	R-Qual	SMUSI	SOBEK-River 1DFLOW	SOBEK-Rural RR	SOBEK-Urban 1DFLOW	STOAT	SULIS	UnTRIM	UTHBAL	Visual Modflow	Waqua
Agricom		M2																							
AM-DSS	M2										M2														
ArcGIS																									
BlueM																									
Delft3D										S4															
GEIWrapper			C5		C5																	C5			
HYMOS																		M3							
Info Works CS									C1,C2,C3,C4,M3,S1											M3					
Info Works RS								C1,C2,C3,C4,S1		S2		S3					M3				M3				
MIKE 11					S4				S2			S3	P1	P2	P1										S4
Mozart	M2	M2																							
PEGASE										S3															
RiSH-1D															P1										
RMM - NTUA																									
R-Qual													P1												
SMUSI				M1																					
SOBEK-River 1DFLOW									M3																
SOBEK-Rural RR																	M3				M3				
SOBEK-Urban 1DFLOW																									
STOAT									M3												M3				
SULIS									M3																
UnTRIM																									
UTHBAL																								P3	
Visual Modflow																									
Waqua										S4															
^ ^ Sending Model																									

Figure 5: Overview of links having been established between OpenMI-compliant models within the reported case studies. The rows and columns of the lower right matrix represent the models which provided and received data respectively (see text for an explanation).

Chapter 5
Other Approaches in Integrated Modelling

Apart from the OpenMI there have been many other attempts in linking models. This chapter gives an overview about these approaches.

Information was mainly taken from the state of the art review from 2002 about existing approaches in integrated modelling [23], which was undertaken within the *HarmonIT* project (see 2.1). The corresponding report can be downloaded from the HarmonIT Homepage (`http://www.harmonit.org`), following the links “Documents > Work package 1”.

In February 2007, the U.S. Environmental Protection Agency (EPA) hosted a workshop on “Integrated Modeling for Integrated Environmental Decision Making”. In the resulting workshop report different “approaches for technology integration and […] the applications and limitations to each approach” were discussed [1, p. 55]. The workshop report was reviewed in order to take a look at approaches used outside Europe and in the United States.

5.1 General

A considerable amount of research has been done to connect or integrate separate numerical models [24]. A revolutionary change that has aided model integration in some cases has been the development of software frameworks which enable that output from one model can become input to the next. Existing frameworks permit the marriage of systems engineering and technology to business and policy [1].

However, many integrated modelling systems were/are not interoperable in this sense; quite often the combination of model components requires a great deal of effort by the modeler. Some level of interoperability is a defining characteristic of integrated modelling [1, p. 19]. Integrated modelling approaches are also challenged by conceptual limitations; these limitations can hamper communication with decision makers.

5.2 Types of approaches

According to [1], approaches for integrated modelling can generally be distinguished according to

- the process of building an integrated system: Top-down approaches versus Bottom-up approaches (see 5.2.1),

- the location, where the separate models are developed, maintained and/or run: Centralized approaches versus Decentralized approaches (see 5.2.2).

All kinds of approaches have limitations. For choosing a proper approach the availability of resources, existing capabilities, the nature and objective of the integration have to be taken into account. The different types of approaches are not mutually exclusive, and a mixture of approaches is both possible and desirable. A mixed approach may be most practical for a large project in which many models are integrated. OpenMI and the Earth Science Modeling Framework (ESMF) by the National Aeronautics and Space Administration (NASA) are essentially mixed approaches in that they allow for less organization from the top [1, p. 56].

In their state of the art review [23] the authors emphasize the distinction between modelling frameworks and integrated models/integrated modelling systems (see 5.2.3)

5.2.1 Top-down approaches versus Bottom-up approaches

Following a *top-down approach* generally means to break down a system into its compositional sub-systems. In a top-down approach an overview of the system is formulated first. This overview contains only the top-level sub-systems. Then, each sub-system is refined in greater detail, and the parts of the sub-systems may in turn be further refined. The process of refinement is repeated until the entire system is specified in terms of base elements. It can sometimes result in many additional subsystem levels.Top-down is often used as synonym of analysis or decomposition. In the sense of integrated modelling, top-down approaches assume that one can define the software integration fully ahead of time. Therefore, it may be too inflexible in many cases. Top-down integration requires the individual components and legacy codes to adapt to a new framework which can be difficult to achieve. Running a simple set of models using a top-down approach requires substantial infrastructure; large-scale systems become especially problematic. It may be difficult to keep an integrated system flexible. A top-down approach, which could be considered as a “command and control” approach, might be most appropriate for new systems or where existing models are limited, with due attention to modularization. [1, p. 55, 56]

In contrast to top-down approaches, *bottom-up approaches* generally put together systems out of sub-systems. First, some base elements are defined in great detail. These elements are then combined to build sub-systems which then in turn are linked, sometimes in many levels, until a complete top-level system is formed. Bottom up is often used as synonym of synthesis. In bottom-up model integration, a framework is built which adapts to the specific model needs. This can result in difficult design issues.

Bottom-up approaches appear to be most scientifically defensible. Basic commonalities or standards, however, must be established at the outset for the various media-specific models to exchange information. A bottom-up approach may be most appropriate for old systems, with existing models to be integrated. [1, p. 56]

Unfortunately, [12] only mentions this general distinction between approaches but does not give examples for modelling systems or frameworks which follow one or the other approach.

5.2.2 Centralized Approaches versus Decentralized Approaches

A *centralized approach* can be useful if participants can virtually access the computing facility and the centralized computing is powerful enough. Modelling systems can be assembled through standardized protocols. Centralization may allow for the use of “community” models such that each group conducts its own integration. Centralized approaches require significant effort [1, p. 56]. The U.S. National Weather Service (NWS) uses a centralized approach for real-time decision making. The NWS Modeling Centers have computing power to perform runs of their centralized models quickly [1, p. 38]

A *decentralized modelling approach* is employed in the U.S. State of Michigan. There, open source models can be chosen from a repository and may be used within more widely distributed development frameworks. Because of decreasing resources the state collaborates with universities. Thus, the different components and contributors leverage each other and the use of modelling frameworks is promoted. Decentralized approaches require an appropriate infrastructure and substantial development [1, p. 38].

5.2.3 Modelling frameworks versus Integrated Models/Modelling Systems

A *modelling framework* is assumed to be generally an ‘open system’ which allows the end user to decide which models to be used [23, p. 18]. Modelling frameworks do not only offer a set of models and mechanisms which enable to combine these models but they allow the linking of further domain modules and swapping of existing ones. Linking models under a common framework means that the legacy models still run as if on their own, but their results are analysed, processed and visualized using tools that are part of a framework. To make legacy models fit into the framework, they may need reprogramming or at least being “wrapped”. In a common framework, the domain models remain functionally separate but they have access to common data. An advantage of a common framework is that all processing tools are available and accessible and that model results can be processed and visualized in a systematic and consistent way [23,

p. 14]. Many of the existing frameworks do not seem to be used outside their own development environment [23, p. ix].

In contrast to a modelling framework, an *integrated model* is supposed to be a system in which selected modules representing different modelling domains are hardwired into a proprietary model management shell. Integrated modelling systems are by far the most common approach to linking models today [23, p. 25]. For example, the InfoWorks modelling software package by Wallingford Software is a drainage modelling system which contains rainfall runoff models, hydraulic models, water quality models, sedimentation models and flow routing models. The individual models are hard wired into the system, allowing consistent access to model parameters and version control. The system aims to provide a single environment that integrates asset planning with detailed modelling [23, p. 29]. Many existing integrated models lack the ability to exchange models of particular domains easily and to use existing models for a particular problem. Integrated modelling systems aim to contain all of the possibly required domain components. [23, p. ix]

5.3 Examples and Comparision of Approaches

5.3.1 Considered Modelling Frameworks and Integrated Models

The HarmonIT state of the art review covers a range of existing modelling frameworks and integrated models. However, because of the numerous approaches having been undertaken in integrated modelling, the review could not be exhaustive [23, p. x].

Table 1 gives an overview of modelling frameworks and integrated models which are covered within the state of the art review. The report presents general descriptions of the frameworks and models and describes the architecture of some of them in detail. Table 1 shows which projects/softwares (first column) are considered as modelling frameworks (second column) or as integrated models (third column) and for which the review contains a description of its architecture (fourth column). Furthermore, the report summarizes initiatives in developing open modelling frameworks (fifth column), grouped into those dealing with water and river basins (marked with ‘w’) and others (marked with ‘o’). Finally, the table shows which of the initiatives for an open modelling framework have been compared and assessed (sixth column, see also 5.3.2).

Table 1: Modelling frameworks and integrated models reviewed in the HarmonIT state of the art review

Project Name [(1)]	**Modelling Framework?** [(2)]	**Integrated Model?** [(3)]	**Description of Archi-tecture?** [(4)]	**Open modelling framework initiative?** [(5)]	**Assessed?** [(6)]
Generic Framework (GF)	x		x	w	x
OMS and Delft Cluster OMS	x				
ICMS/TARSIER and TIME	x		x	w	
DIAS	x		x	w	x
IDLAMS/OO-IDLAMS	x				
MIMS	x				
MMS	x			w	x
MODELS-3	x				
DelftWISE	(x)		x	w	
EUROTAS	(x)	fm		w	x
MIKE SHE	(x)	wm		w	
MIKE BASIN		wm			
MIKE System Developments			x		
BASINS	(x)			w	x
SMS	(x)	wm		w	x
FloodWorks		ff	x		
InfoWorks		dm	x		
EFFS/DelftFEWS		ff	x		
THETIS	(x)		x	o	x
DESIMA	(x)		x	o	x
ARION	(x)		x	o	x
ELTRAMOS	(x)			o	x
MDSF		ff			
SWAT		wm			
UPM		dm			
MODULUS		em			
IRMA-SPONGE/ DSS Large Rivers		em			

(1) Name of project/software
(2) x: The project is described in chapter “Modelling Frameworks” of the review.
(x): The project is not described in chapter “Modelling Frameworks” but considered as an initiative in open modelling frameworks
(3) If not empty, the project is treated as an Integrated Model, namely a
ff: flood forecasting system,
fm: flood management model,
wm: watershed model,
dm: drainage model
em: ecological/economic model.
(4) x: The review contains a description of the architecture of the model/modelling framework
(5) If not empty, the project is listed as an initiative in developing an open modelling framework.
w: The initiative deals with water/river basin type problems
o: The initiative deals with other problems
(6) x: The project has been subject to an assessment and a comparison between modelling frameworks (see 5.3.2)

5.3.2 Assessment of several Modelling Frameworks

In general, the authors of the state of the art review state that the Australian framework TIME is considered to have similar goals as the HarmonIT project. They recommend that the development of the TIME project should be followed [23, p. 22]. The structure and architecture of the MODELS-3 modelling system is also considered to be worth looking at [23, p. 24].

The “Open modelling framework initiatives” (see fifth column of Table 1) were compared with regard to different development, performance and applicability aspects. The result of the comparison is shown in Table 2 (taken from [23, p. 71] with +++: very good example, ++: good example, +: example of some use, empty field: poor example).

Table 2: Results of a comparison between modelling frameworks (see [23, p. 71])

	Per-formance	**Reengi-neering**	**Open**	**Accepted standard**	**Widely used, robust, extensive implemen-tation**	**Models easily added**	**Full user interface**
GF	++	++	+++	+	+	++	
EUROTAS			+++	+++	+		++
MMS			+++	+++		++	
BASINS				+++			
DIAS	++		+++		++	++	++
SMS	+++						+++
ARION			+++	+++			
THETIS			+++				+++
DESIMA							+++
ELTRAMOS							

The authors of the review conclude that all of the frameworks (except ELTRAMOS) appeared to have some valuable concepts but none of them seemed to be a system which met all the requirements for an open modelling framework in the water management domain. Most of the frameworks (except GF) appeared to be poor in terms of reengineering, i.e. they require substantial recoding of existing software to allow integration within the framework. Except possibly DIAS the frameworks appeared to be not widely used.

When the state of the art review was published in 2002, none of the existing frameworks for linking models has been widely accepted or applied. This may have been due to

- the development process in which only one or a small number of organisations are involved,
- limitations in the frameworks themselves,

- a focus on functionality rather than architecture,
- the absence of an open and published standard [23, p. x].

Chapter 6
Summary and Conclusions

Within the project SAM-CSO it shall be tested if the Open Modelling Interface and Environment (OpenMI) can be applied to link models of the Berlin sewerage (modelled in the urban drainage software InfoWorks CS,Wallingford Software) to a river water quality model.

This report gives an overview on the OpenMI and its application. *Chapter 1* outlines the general background of integrated water management and integrated modelling as it is aimed at by the European Water Framework Directive. The development process, which resulted in the release of the OpenMI is summarized in *chapter 2*. An introduction to the objectives, the concept and the technology of the OpenMI is given in c*hapter 3*. *Chapter 4* lists case studies in which the OpenMI has been applied. In Appendix B, each of the reported studies has been described in generalized form. A matrix showing all model links, which have been established within the case studies, has been developed. Finally, in *chapter 5*, an overview on other model linking approaches is given.

This report shows that in many use cases the Open Modelling Interface could be used successfully for model linking. Even out of Europe, at a workshop of the U.S. EPA it is stated that, in terms of the ability to go between different temporal and spatial scales, a framework such as OpenMI might have the necessary flexibility. Actually, it was found that in many cases models of the InfoWorks software family have been part of the OpenMI linked systems.

In cases of many interaction points between models, the OpenMI mechanism may not be applicable. In the Berlin case the impact of combined sewer overflows on the water quality of the receiving river shall be examined. With far less than a hundred interaction points between sewer model and river model it is assumed that the OpenMI could be used for a successful model linking. The difficulty within the SAM-CSO project may be to find an apropriate river quality model, which is ready to be linked to InfoWorks CS using the OpenMI. Unfortunately, there are few use cases reported in which a freely available river water quality model was involved. The water quality model QSIM of the German Institute of Hydrology (BfG) that is used within the project is currently not equipped with OpenMI.

Nevertheless, using the OpenMI mechanism for model linking is assumed to be a promising approach. It is expected to become an internationally accepted standard. As the OpenMI specification is fully free, anyone may contribute to its further development. The OpenMI Association will give advice to modellers and will be open to discussions on improvement of the OpenMI.

With the OpenMI linking mechanism not only models can be linked. Modules for calibration, optimization, statistical evaluation etc. can be part of an OpenMI system as well as components for generic data access or visualization. It will be tested, if the integration of such a module for statistical evaluation into the CSO impact assessment method (to be developed within the project SAM-CSO) is applicable and useful.

Appendix A

HarmonIT and OpenMI-LIFE Participants

Company Name	Country	Harmon IT	OpenMI-LIFE
Alterra B.V.	Netherlands	x	
Aquafin NV	Belgium		x
Agricultural and Environmental Engineering Research (Centre National du Machinisme Agricole, du Genie Rural, des Eaux et des Forets (Cemagref))	France	x	
DHI Water and Environment (former: Danish Hydraulic Institue)	Denmark	x	x
DHI Hydroinform a.s.	Czech Republic	x	
Flanders Hydraulic Research	Belgium		x
Hydropojekt CZ a.s.	Czech Republic	x	
National Research Council of Italy (Instituto di Ricerca Sulle Acque (IRAC))	Italy	x	
Flemish Environment Agency (Intern Verzelfstandigd Agentschap Vlaamse Milieumaatschappij (VMM))	Belgium		x
Flemish Environment Agency / Division Water (Intern Verzelfstandigd Agentschap Vlaamse Milieumaatschappij / Afdeling Water (VMM-AWA)]	Belgium		x
Flemish Environment Agency / Division Quality Management (Intern Verzelfstandigd Agentschap Vlaamse Milieumaatschappij / Afdeling Kwaliteitsbeheer (VMM-AK))	Belgium		x
Natural Environment Research Council (NERC) / Centre for Ecology and Hydrology (CEH)	United Kingdom	x	x
National Technical University of Athens (NTUA) / Centre of Hydrologic Information (CHI)	Greece	x	x
Povodi Labe, s.p.	Poland	x	
National Institute for Coastal and Marine Management (RIKZ)	Netherlands		x
Dutch Ministry of Transport, Public Works and Water Management / Institute for Inland Water Management and Waste Water Treatment (Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling (RIZA))	Netherlands	x	
University of Liège / Environmental Modelling Centre (Université de Liège / Centre d'Etude et de Modélisation de l'Environnement (CEME))	Belgium		x
University of Dortmund	Germany	x	
University of Thessaly	Greece		x
WL	Delft Hydraulics (Stichting Waterloopkundig Laboratorium (WL))	Netherlands	x	x
WRc plc	United K.	x	
Wallingford Software Ltd (HR Wallingford Group Ltd)	United K.	x	x

Appendix B
Case Studies

B.1 Case Studies C1 to C6

B.1.1 Case Study C1 [25]

<table>
<tr><td>Topic</td><td>Flood risk mapping study of the Havant catchment</td></tr>
<tr><td>Team</td><td>WS Atkins plc, commissioned by the Environment Agency's Southern Region</td></tr>
<tr><td>Runtime</td><td>January 2006 – December 2006</td></tr>
<tr><td>Catchment</td><td>

Havant catchment in the county of Hampshire, UK
Main river outfalls to a harbour.
Two main sub-catchments of main streams Lavant (60 km²) and Hermitage (20 km²)
Ca. 50 % rural, the rest is heavily urbanized (including Havant town
Havant catchment has many long culverted reaches.
Pipe acting as flood relief culvert diverts flows Lavant Stream to Hermitage Stream
Two further important culverts of 1200 m and 600 m.

</td></tr>
<tr><td>Motivation</td><td>Floods in the Havant catchment are caused by overtopping of the open channel sections, mainly when river levels (and consequently groundwater flows) are very high and by overwhelming of surface water drains from the urban areas attempting to discharge during intense rainfall events. High river levels are among others induced by these surface water outfalls to the river.</td></tr>
<tr><td>Objectives</td><td>

Flood risk mapping study of the Havant catchment
Flooding as an integrated problem.

</td></tr>
<tr><td>Challenges</td><td></td></tr>
<tr><td>Models</td><td>
<table>
<tr><td>Model</td><td>A</td><td>B</td></tr>
<tr><td>Type</td><td>Rainfall runoff and sewage</td><td>River flow</td></tr>
<tr><td>Software</td><td>InfoWorks CS</td><td>InfoWorks RS</td></tr>
<tr><td>Schematization</td><td>Culverted reaches and pipes</td><td>River reaches
16 km stream length
high level of detail
280 river cross-sections
50 modelled structures</td></tr>
<tr><td>Use</td><td></td><td></td></tr>
<tr><td>Responsible</td><td></td><td></td></tr>
<tr><td>(Orig.) Timestep</td><td></td><td></td></tr>
</table>

Two flows (representing two link culverts) from “B” into “A” and four outflows from “A” back into “B”.
An area in the town centre has a complex hydraulic profile of an open channel moving into culverted sections and then back into open channel.
190 outfalls from the surface water systems into the river channels were identified

</td></tr>
<tr><td>Actions</td><td>Software Changes

InfoWorks is already OpenMI-compliant (since version 8.0)

</td></tr>
</table>

	Schematization/Data Changes - 190 outfalls were grouped into 30 discrete outfalls to enable OpenMI to work - Sewerage in sub-catchments were simplified to minimise model run-time **Links** - Connections between "A" and "B" are bi-directional - Flow series is passed from "A" into "B", and a level series is passed back from "B" to "A" at the outfall points. - Another flow series from the flood relief culverts where again flow and level data are being passed between the two models, but in the opposite direction.
Results and Conclusions	**General/conceptual/standard specific** - With OpenMI, models could be linked effectively. - Interactions could be accounted for with only one concurrent run of each model rather than a number of times using a manual, possibly error-prone cut-and-paste procedure → OpenMI improved efficiency and accuracy - Work is still needed to lower some minimum flows added for model stability. - With OpenMI, catchment could be modelled more detailed than normal → output will be more accurate than normally achieved in flood risk analysis - The model complexity did not prove to be an issue. - By including the urban areas flooding issues within these areas could easily be investigated rather than just their contributions to the river systems. - OpenMI will allow a quick calibration with a minimum number of model runs. - OpenMI provides a collaborative tool that will enable stakeholders to begin to communicate – regulators, water companies, local authorities, highways authorities and developers. - OpenMI will allow to look at problems in an integrated manner and to find integrated, holistic solutions. **Software specific** **Scenario specific**

B.1.2 Case Study C2 [26]

<table>
<tr><td>Topic</td><td>Real Time Control Using OpenMI</td></tr>
<tr><td>Who?</td><td>Wallingford Software</td></tr>
<tr><td>When?</td><td>Reported: 24 November 2006</td></tr>
<tr><td>Catchment</td><td>
- Bournemouth: large coastal resort town (163,000 inhabitants in 2001) in Dorset, England.
- Several large sewage pumping stations → 5 km long coastal interceptor sewer → wastewater treatment plant (WWTP) → treated effluent is discharged via long sea outfall.
- Additionally, combined sewer outflows (CSO) discharge during storm events.
- Target: minimize the pollution of the receiving river → Bournemouth's catchment is monitored by extensive real-time control (RTC) system.
- This system controls the sewer system depending on conditions in the river where the sewer discharges. The main component is a storage tunnel, where flows are stored by activating a penstock depending on flow conditions in WWTP.
- The penstock's activation and the flow through the works is also based on ammonia concentrations. Sampling devices at the WWTP measure the amount of ammonia in the flows from the storm tanks, as well as the treated effluent concentrations and flow rates. From these data, the ammonia concentration in the River Stour is derived by a simple mass balance equation, taking into account river flows.
- Penstock is opened or closed depending on whether the results determine that levels of ammonia in the river will be above or below a certain target value.
</td></tr>
<tr><td>Motivation</td><td>
- Initial modelling of the complex RTC was in HydroWorks.
- Using a complex empirical matrix, the corresponding model was inflexible. Variables (e.g. river flow, ammonia concentration) could not be changed.
- Despite of being already very complex, RTC system could not model the spill flows in th desired detail.
</td></tr>
<tr><td>Objective</td><td>
- River water quality should determine the amount of flow that could either be passed through the WWTP or should be retained in the sewer system.
- Study how different storms would affect the ammonia concentration and the WWTP performance → Dynamic sewer network model (InfoWorks CS)
- Achieve highly-sensitive RTC system by properly linking the RTC to the river ammonia concentrations → parallel integrated catchment simulation → river and sewer model should run together with timestep by timestep feedback of data
</td></tr>
<tr><td>Models</td><td>
<table>
<tr><td>Model</td><td>A</td><td>B</td></tr>
<tr><td>Type</td><td>Wastewater model</td><td>River model</td></tr>
<tr><td>Software</td><td>InfoWorks CS</td><td>InfoWorks RS</td></tr>
<tr><td>Schematization</td><td>Urban areas and RTC system</td><td>simple model of River Stour</td></tr>
<tr><td>Use</td><td></td><td></td></tr>
<tr><td>Responsible</td><td></td><td></td></tr>
<tr><td>(Orig.) Timestep</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Actions</td><td>
Software Changes
- InfoWorks is already OpenMI-compliant (since version 8.0)
Schematization/Data Changes
- The data from the HydroWorks model were transferred into InfoWorks CS.
</td></tr>
</table>

	- In "A", all of the flows going through the WWTPs were represented as a constant trade flow with a constant ammonia concentration. Two outfalls leading from the WWTP were modeled.
	- The storage tanks and the point where all the flows exited "A" were modeled. Storm flows through the tanks and spill to the river were represented dynamically by "A"
	- "B" was created from cross-section data and a ground model. This had two boundary nodes:
	  - constant river flow with a conservative pollutant concentration.
	  - point where flow and ammonia levels from "A" enter "B"
	- In "A", an RTC system can only be controlled from a link within the model itself → New dummy river link in "A" which will accept data from "B" and which will be used to control the penstock
	
	Links
	- Transfer of flow and pollutant data from "A" to "B"
	- Feedback of data from "B" back to the dummy river link in "A"

Results and Conclusions	**General/conceptual/standard specific** - By linking "A" and "B", it was possible to examine all of the variables that had been impossible to examine previously, and undertake a range of modelling not previously possible. - Flows were calculated as expected → confidence in the linking process - The linking required some lateral thought: it was important to remember to include a dummy river link in "A". - Units can vary between the two models → need to check results carefully. **Software specific** **Scenario specific** - The ammonia results did show that the RTC was able to control the penstock in order to reduce flows and to maintain the target ammonia concentration in the river. - OpenMI can be used for integrated catchment modelling with RTC, and to represent the link between river pollutant concentration and control of the sewer system flows.

B.1.3 Case Study C3 [5, 27]

<table>
<tr><td>**Topic**</td><td>Flood estimation with InfoWorks CS and InfoWorks RS</td></tr>
<tr><td>**Team**</td><td>Wallingford Software, Ewan Group plc</td></tr>
<tr><td>**Runtime**</td><td>Reported: 2006</td></tr>
<tr><td>**Catchment**</td><td>- Kenilworth: mainly-residential market town in the West Midlands of England.
- Surrounding land: mainly agricultural.
- Total area: 750 ha, total population: 14,000.
- Sewer network: predominantly separate system, only few combined systems
- Three main open channels in the town as well as the urban drainage system, which interacts with the rivers
- Main feature of sewerage in Kenilworth: triple sewer system (original town system, a later, duplicate system, and relief sewers)
- Terminal pumping station transfers flows to wastewater treatment plant (WWTP)
- The three sewers are interconnected along their lengths, with many branches → Kenilworth sewers form a hydraulically-inadequate looped network with complex flows.</td></tr>
<tr><td>**Motivation**</td><td>- Large scale flooding issues from various sources.
- In order to meet requirements set out by the Environment Agency a combined sewer overflow (CSO) had to be added to the catchment.
- Originally: three separate models for sewerage catchment and for receiving watercourses. River model calculated river levels which were manually fed into the sewerage model to obtain an estimate of their impact. Unless a laborious iterative approach to this manual transfer is adopted not all feedback interactions are accounted for.
- However, assessing the impact of sewerage discharges and overland flows from urban areas to watercourses and the subsequent effects of watercourse levels on the sewerage system requires an holistic approach to modelling.</td></tr>
<tr><td>**Objectives**</td><td>- By using OpenMI a more accurate estimate of the interactions between the watercourses and sewers should be obtained.</td></tr>
<tr><td>**Models**</td><td>
<table>
<tr><td>Model</td><td>**A**</td><td>**B**</td></tr>
<tr><td>Type</td><td>Sewer flow model</td><td>River flow model</td></tr>
<tr><td>Software</td><td>InfoWorks CS</td><td>InfoWorks RS</td></tr>
<tr><td>Schematization</td><td>Sewer system with only one CSO: the overflow from the storm tanks at the terminal pumping station.</td><td></td></tr>
<tr><td>Use</td><td></td><td></td></tr>
<tr><td>Responsible</td><td></td><td></td></tr>
<tr><td>(Orig.) Timestep</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>**Actions**</td><td>**Software Changes**
- InfoWorks is already OpenMI-compliant (since version 8.0).

Schematization/Data Changes
- “A” was created, with points indicating the outflows to the rivers, a WWTP and its outfall downstream.
- One of the rivers which accepts and transfers urban stormwater discharges is represented within the model.
- As part of the new sewerage strategy, a further overflow was added.
- The rivers which were originally modeled in HEC-RAS were transfered to InfoWorks RS.</td></tr>
</table>

	Links - Interactions between "A" and "B" were established via 17 bi-directional links at points where sewerage network provided inflow to the river. - "A" simulated the flows at the links which were taken as boundary conditions in "B". "B" itself calculated the water levels along the river sections. The resulting river levels at the outfalls were used as input to "A"
Results and Conclusions	**General/conceptual/standard specific** - OpenMI is a useful tool in linking different hydraulic models. - OpenMI could be used to simulate water level interactions between sewerage and receiving water within one simulation run → The linking of models increased the ability to understand the complex hydraulics. - The OpenMI environment enabled the linking of a monitor model which could be used to investigate the data values being passing between the models. - Stability and search functions of the OpenMI environment require improvement, especially for large models. **Software specific** - OpenMI could combine InfoWorks CS and RS in an urban environment to represent flooding interactions within one simulation run. **Scenario specific** - Influenced by the overflow discharges the downstream river levels in the river model were high for longer than had been predicted when the models were run separately and no feedback was represented in the model. - Integrated model lead to a more accurate representation of urban flooding, CSO spills and river characteristics.

B.1.4 Case Study C4 [28]

<table>
<tr><td>Topic</td><td>Integrated modelling in Japan using InfoWorks and OpenMI</td></tr>
<tr><td>Team</td><td>Chuou Sekkei Engineering, Japan</td></tr>
<tr><td>Runtime</td><td>May 2007 to August 2007</td></tr>
<tr><td>Catchment</td><td>- Study area is located at the northern part of the Kyoto prefecture
- Focus: downstream area of the medium-sized river within the area</td></tr>
<tr><td>Motivation</td><td>- Need to carry out a flooding study.</td></tr>
<tr><td>Objectives</td><td>- Integrated modelling study
- Represent in one environment flooding from sewage systems and rivers more realistically, in particular in situations in which flooding from sewage systems occurs first and then combines with flooding from rivers.</td></tr>
<tr><td>Models</td><td>
<table>
<tr><td>Model</td><td>A</td><td>B</td></tr>
<tr><td>Type</td><td>Sewer flow model</td><td>River flow model</td></tr>
<tr><td>Software</td><td>InfoWorks CS</td><td>InfoWorks RS</td></tr>
<tr><td>Schematization</td><td></td><td></td></tr>
<tr><td>Use</td><td></td><td></td></tr>
<tr><td>Responsible</td><td></td><td></td></tr>
<tr><td>(Orig.) Timestep</td><td></td><td></td></tr>
</table>
- Reasons for model choice: sophisticated representation of results in InfoWorks and the ongoing development plan for the InfoWorks family of products.</td></tr>
<tr><td>Actions</td><td>Software Changes
- InfoWorks is already OpenMI-compliant (since version 8.0)
Schematization/Data Changes
- Originally a model in InfoWorks CS existed for the area, but over time corrections were made to the model and an RS model was also newly built for this project.
Links
- Integration of “A” and “B” in two phases:
1. Data exchanges between outfalls in “A” and water levels at the corresponding river cross-sections in “B”
2. Spilled water at manholes in “A” and water levels of floodplain areas in “B”</td></tr>
<tr><td>Results and Conclusions</td><td>General/conceptual/standard specific
- With OpenMI, it was managed to carry out integrated simulations in such a way that the integrated results achieved something that could not have been achieved within one modelling system alone.
- OpenMI was easy to use and took little time to understand.
- It was difficult to decide which parameters to join between InfoWorks CS and InfoWorks RS, especially for flooding in floodplain areas.
Software specific
- The OpenMI tutorials and the technical support supplied by Wallingford Software were sufficient for understanding the OpenMI (Environment).
Scenario specific
- Project was first successful example of integrated modelling with OpenMI in Japan.
- Flooding from rivers tends to be huge, compared with flooding from the sewage network → choice of target areas could be important.</td></tr>
</table>

	- Results have proved a useful way to represent flooding from both sewage systems and rivers in a single environment.

B.1.5 Case Study C5 [29-31]

<table>
<tr><td>Topic</td><td>Import of initial and boundary data from BAW formats into Delft3D and ArcGIS</td></tr>
<tr><td>Team</td><td>- Coastal Department and software group (ProgHome) of the Federal Waterways Engineering and Research Institute (Bundesanstalt für Wasserbau – BAW), Germany</td></tr>
<tr><td>Runtime</td><td></td></tr>
<tr><td>Catchment</td><td>- NorthSea, Ems and Elbe Estuary</td></tr>
<tr><td>Motivation</td><td>- Traditional way to import data into a numerical engine is to convert the data into the appropriate format before runtime.
- Using OpenMI as an open interface standard can achieve a more generic approach</td></tr>
<tr><td>Objectives</td><td>- Develop an OpenMI compliant “Data Reader” (GEIWrapper) for reading data in proprietary formats, which are used at the BAW (BAW data formats)
- The Reader shall be easily reused by different (OpenMI compliant) components
- Especially, the Reader shall allow the import of BAW data into
  - the Geographical Information System ArcGIS
  - Delft3D-FLOW (initial and boundary data)
  - UnTRIM</td></tr>
<tr><td>Challenges</td><td></td></tr>
<tr><td>Models</td><td>
<table>
<tr><td>Model</td><td>A</td><td>B</td><td>C</td><td>D</td></tr>
<tr><td>Type</td><td>Database</td><td>Geo-information system</td><td>Numerical Engine</td><td>Numerical Method</td></tr>
<tr><td>Software</td><td>GEIWrapper</td><td>ArcGIS</td><td>Delft3D-FLOW</td><td>UnTRIM</td></tr>
<tr><td>Schematization</td><td></td><td></td><td>Ems Estuary</td><td>Ems Estuary</td></tr>
<tr><td>Use</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Responsible</td><td>BAW</td><td></td><td>WL | Delft Hydraulics</td><td></td></tr>
</table>
- “A” serves as a database accessing data stored in proprietary BAW file formats. It is not a stand-alone executable.</td></tr>
<tr><td>Actions</td><td>Software Changes
- “A” is a newly created component which is OpenMI compliant.
- “B”, “C” and “D” have been made OpenMI compliant.
Schematization/Data Changes
- To enable a comparision between “C” and “D”, they share the same section of the Ems Estuary.
Links
- The OpenMI Configuration Editor can be used to build a composition to import data (e.g. boundary and initial data) from “A” to “B”, “C” or “D”:
  - “A” and “B”/”C”/”D” must be added to the editor before.
  - Then the user establishes links between the components having free choice which exchange items to select.
- “A” offers data (e.g. initial and boundary data) as an output.</td></tr>
</table>

	- "B", "C", "D" or other OpenMI-compliant components accept this data as an input.
Results and Conclusions	**General/conceptual/standard specific** **Software specific** - The OpenMI compliant GEIWrapper is able to read proprietary BAW data and to feed it into other OpenMI compliant components like ArcGIS, Delft3D and UnTRIM. - Re-using the GEIWrapper simplifies the process of making existing software able to access BAW data. **Scenario specific** - OpenMI can help to simplify data import into modelling softwares. Data can be directly imported from proprietary files without the need to an intermediate output into the format of the numerical engine. - Conversions and temporal and spatial interpolations are automatically done by the application at runtime - Model comparisons and multi model forecasts benefit from OpenMI due to the fact that using the Reader different (OpenMI compliant) models (here: comparision between UnTRIM and Delft3D-FLOW) can import the same files. - Already existing files which have been generated for import into other numerical engines can be re-used. - Generic approach means that the numerical engine can easily be replaced by another one and that the data reader can be replaced as well. - The user can steer the import and the simulation itself with the OpenMI configuration editor. Connections between components can be established by mouse click.

B.1.6 Case Study C6

For the case study C6: "Surface-Groundwater Interactions Using the OpenMI by Johan Hartnack" no further information could be found.

B.2 Case Studies S1 to S4

B.2.1 Case Study S1: Scheldt Use Case A [32]

<table>
<tr><td>Topic</td><td>Impact of sewer discharges on the receiving river during flooding [33]</td></tr>
<tr><td>Team</td><td>Aquafin, Belgium
Flemish Environment Agency, Division Water (VMM-AWA), Belgium</td></tr>
<tr><td>Runtime</td><td>OpenMI-LIFE: 2006 – 2009</td></tr>
<tr><td>Catchment</td><td>- City of Leuven (90,000 inhabitants)
- River Dijle (contributary to the river Scheldt)
- Sewer system of Leuven discharges into the river Dijle</td></tr>
<tr><td>Motivation</td><td>- Sewer peak discharges during wet weather → flood management in the rivers severely affected.</td></tr>
<tr><td>Objectives</td><td>- Overall: optimize investments and operational strategies of sewer and river managers.
- More accurate flood maps → integrated modelling approach needed
- Find locations where excess storm water from sewer system can be discharged safely (without flooding).
- Better understand two way interactions between sewer and river.
- Consider not only flows and water levels but also flood volumes as exchanged quantities
- InfoWorks (see “Models” below) specific:
  - Find out how linkage of InfoWorks CS and InfoWorks RS will affect version management in both systems.
  - Assess collaboration with model developer (Wallingford Software), e.g. in terms of response time, when software update needed</td></tr>
<tr><td>Challenges</td><td>- Understand existing modelling procedures and objectives and try to harmonise them [17],
- Flow, level and flood exchange at appropriate links,
- Incorporation of flow links in river calibration.</td></tr>
<tr><td>Models</td><td>
<table>
<tr><td>Model</td><td>A</td><td>B</td></tr>
<tr><td>Type</td><td>Sewer flow model</td><td>River flow model</td></tr>
<tr><td>Software</td><td>InfoWorks CS</td><td>InfoWorks RS</td></tr>
<tr><td>Schematization</td><td>drainage area “Leuven”</td><td>(Part of) River Dijle</td></tr>
<tr><td>Use</td><td>optimal hydraulic sewer design</td><td>flood risk map creation and operational model for flood risk prediction</td></tr>
<tr><td>Responsible</td><td>Aquafin</td><td>VMM-AWA</td></tr>
<tr><td>(Orig.) Timestep</td><td>60 s</td><td>100 s (variable)</td></tr>
</table>
- Different degrees of detail in “A” and “B” [17], e. g. “A” needs higher resolution of rainfall intensities than “B”
- Differences in timesteps
- More than 100 interaction points [17]</td></tr>
<tr><td>Actions</td><td>Software Changes
- InfoWorks is already OpenMI-compliant (since version 8.0)
Schematization/Data Changes
- Define boundary conditions and timesteps for “A” and “B”
- Remove model overlappings (river sections modeled in “A” and urban areas modeled in “B”)</td></tr>
</table>

	- Include new boundaries in "B" to allow links to be made (Some discharge points were modeled only in "A" but not in "B".).
	
	Links
	- Establish two types of links:
	  - Transfer of flows from "A" to "B" at discharge points (permanent outfalls, overflows, treatment plant),
	  - Transfer of water levels from "B" back to "A" at discharge points to prevent free discharge.
	- Further link planned:
	  - Exchange of flood levels and volumes between manholes near to river flood zones in "A" and the river flood zone in "B"

Results and Conclusions	**General/conceptual/standard specific**
	- OpenMI technically works [17]
	- Linking as such seems to work OK [33]
	  - Actual exchange highly dependent on model content
	  - Important to analyse results carefully
	- OpenMI can handle differences in timesteps (best to choose multiples in order to avoid too much interpolations) [17]
	- Performance may still be a problem for large models and large amounts of links [17]
	- Remote linking (preferred for the future) today (September 2007) not yet available [17]
	- Various conceptual/practical issues still have to be solved [33]
	- Technical problems are gradually being solved [33]
	
	Software specific
	- Original OpenMI-implementation of InfoWorks RS fails to load/run large models → new implementation needed [17]
	- Exchange of flood volumes foreseen in OpenMI implementation of InfoWorks? [17]
	
	Scenario specific

B.2.2 Case Study S2: Scheldt Use Case B [34]

<table>
<tr><td>Topic</td><td>Influence of river flow regulations (by dredging) on flood risk in a river</td></tr>
<tr><td>Team</td><td>Flanders Hydraulic Research (FH), Belgium
Flemish Environment Agency (VMM-AWA), Belgium</td></tr>
<tr><td>Runtime</td><td>OpenMI-LIFE: 2006 – 2009</td></tr>
<tr><td>Catchment</td><td>Catchment of the river Dijle, a contributary to the river Scheldt.</td></tr>
<tr><td>Motivation</td><td></td></tr>
<tr><td>Objectives</td><td>- Does linking of river models help for integrated water management?
- Improve flood frequency maps and enable flood forecast
- Study influence of river flow regulations (downstream and upstream) on flood risk in river by model linking
- Improve dynamic data exchange at model boundaries
- Use Case specific:
  - Demonstrate that two-way interactions of flows and water levels between two river systems can be modelled by means of a runtime link between two modells
- Assess practical feasability:
  - large scale model linking
  - problems with large result files (iterations while data exchange)?
  - version management in model softwares affected?</td></tr>
<tr><td>Challenges</td><td>- Assess feasibility (data handling, simulation times) of large scale model linking,
- Find appropriate locations for model interactions
- Finding appropriate historical events which address various combinations of high/low flows for the non-tidal part and high/low tides for the tidal section,
- Remote linking possible? (Useful for forecasting).</td></tr>
<tr><td>Models</td><td>
<table>
<tr><td>Model</td><td>A</td><td>B</td></tr>
<tr><td>Type</td><td>Non-tidal river (flow) model</td><td>Tidal river (flow) model</td></tr>
<tr><td>Software</td><td>InfoWorks RS</td><td>Mike-11</td></tr>
<tr><td>Schematization</td><td>Upstream Dijle (105 km), 2*106 m3 natural flooding, artificial reservoir (106 m3)</td><td>Downstream Dijle – Scheldt (160 km)</td></tr>
<tr><td>Use</td><td>With historical rainfall events</td><td>With composite hydro-grams specific for return period</td></tr>
<tr><td>Responsible</td><td>VMM-AWA</td><td>FH</td></tr>
<tr><td>Timestep</td><td>100 s</td><td>300 s</td></tr>
</table>
</td></tr>
<tr><td>Current practice</td><td>- “A” needs downstream boundary (water level, influenced by tides and by flood areas further downstream). “A” used level timeseries (interpolated from short term measurements).
- “B” lacks information about impact of management of flood areas in “A”. “B” used predicted flow timeseries or simple hydrological model.</td></tr>
<tr><td>Actions</td><td>Software Changes
- None, as InfoWorks and Mike-11 are already OpenMI-compliant</td></tr>
</table>

<table>
<tr><td></td><td>Schematization/Data Changes
- In order to define links or to avoid overlapping input:
  - Remove nodes
  - For linking flood plains on flood conditions → changes necessary, e. g. new nodes/flood areas in “B” (dummy storage areas?)
  - Add Q boundary

Links
- Link in the area of the confluence of Dijle and Demer
- Large set of possibilities of cutting and linking the models → 4 combinations (linking schemes) were selected (with 1 or 3 links between “A” and “B”)
- Link of “A” and “B” will provide a downstream boundary for “A” and an upstream boundary for “B”
- Bi-directional link:
  - Flow from “A” to “B”
  - Stage from “B” to “A”
  - Flow in storage area from “A” to “B”
  - Stage in flood area from “B” to “A”

Scenarios
- Test linked system with data of historical periods with different combinations of flow and tides</td></tr>
<tr><td>Results and Conclusions</td><td>General/conceptual/standard specific
- OpenMI may have problems with large models [34, p. 7]
- To make time step exchangeable: one should be multiple of another
- Using different timesteps for linked models led to different results compared to using same time step

Software specific
- Omi-files produced by InfoWorks RS not always accepted by OpenMI
- New InfoWorks version (8.5) is able to upload and run the large model “A” [35]
- Linking of flooding areas at the confluence remains a future issue (Nov 2007) [35]

Scenario specific</td></tr>
</table>

B.2.3 Case Study S3: Scheldt Use Case C [36]

<table>
<tr><td>Topic</td><td>Effect of flow regulations on water quality and impact of water quality during flooding</td></tr>
<tr><td>Team</td><td>Flanders Hydraulic Research (FHR), Belgium
Flemish Environment Agency (VMM-AWA and VMM-AK), Belgium
University of Liège / Environmental Modelling Centre (ULG-CEME), Belgium</td></tr>
<tr><td>Runtime</td><td>OpenMI-LIFE: 2006 – 2009</td></tr>
<tr><td>Catchment</td><td>- Dijle river basin in the Belgian Flemish region
- Area: 1,276 km², Population: 560,000</td></tr>
<tr><td>Motivation</td><td></td></tr>
<tr><td>Objectives</td><td>- Support integrated water policy scenarios
- Study effect of water flow regulations on water quality and the impact of water quality during flooding
- Improve modelling of interactions between different related water domains (hydrologic, hydraulic, quality)</td></tr>
<tr><td>Challenges</td><td>- Differing discretisation between the models,
- Selecting appropriate links and exchange time steps respecting the different spatial and temporal domains, which the models are applied on.</td></tr>
<tr><td>Models</td><td>
<table>
<tr><td>Model</td><td>A</td><td>B</td><td>C</td></tr>
<tr><td>Type</td><td>River flow model</td><td>River flow model</td><td>River quality model</td></tr>
<tr><td>Software</td><td>InfoWorks RS</td><td>Mike-11</td><td>PEGASE</td></tr>
<tr><td>Schematization</td><td>River Dijle, non-tidal parts</td><td>River Dijle, tidal parts</td><td>River Dijle, Walloon part</td></tr>
<tr><td>Use</td><td></td><td></td><td></td></tr>
<tr><td>Responsible</td><td>VMM-AWA</td><td>FHR</td><td>VMM</td></tr>
<tr><td>(Orig.) Timestep</td><td></td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Actions</td><td>Software Changes
- InfoWorks supports OpenMI since version 8.0
- Pegase has to be made OpenMI-compliant (planned until March 2008) [19]
Schematization/Data Changes
- New description of river Dijle in “C” (in order to let it match with descriptions in “A” and “B”) [19]
Links
- Two sub-cases:
  - linking A to C (only a few discrete nodes) [36, p. 18]
  - linking B to C (all available nodes)
- Only one-directional links, but bi-directional links between B and C shall be tested.
Scenarios</td></tr>
<tr><td>Results and Conclusions</td><td>General/conceptual/standard specific

Software specific

Scenario specific</td></tr>
</table>

B.2.4 Case Study S4: Scheldt Use Case D [37]

<table>
<tr><td>Topic</td><td>Influence of tides on upstream flood risk</td></tr>
<tr><td>Team</td><td>- National Institute for Coastal and Marine Management (RIKZ), Netherlands,
- WL | Delft Hydraulics, Netherlands,
- Flanders Hydraulic Research (FH), Belgium</td></tr>
<tr><td>Runtime</td><td>OpenMI-LIFE: 2006 – 2009</td></tr>
<tr><td>Catchment</td><td>- From the Flemish part of the River Dender to the Western Scheldt estuary</td></tr>
<tr><td>Motivation</td><td>- Models with different extend and detail at different Authorities → no integrated policy or management until now</td></tr>
<tr><td>Objectives</td><td>- Study influence of tides to upstream flood risk
- Main management and policy issues are to improve
  - Boundary conditions within each model
  - Flood maps and flood forecasting during storm surges and/or high inland discharges
  - Discharge and velocity distribution in Westerscheldt due to high inland discharges
  - Accessibility of Antwerp Harbour and forecast of Accessibility</td></tr>
<tr><td>Challenges</td><td>- Translation of the 1-D discharge and water level from Mike-11 (see “Models below) to 2-D or 3-D discharges and levels in the Waqua or Delft3D grid</td></tr>
<tr><td>Models</td><td>
<table>
<tr><td>Model</td><td>A</td><td>B</td><td>C</td></tr>
<tr><td>Type [17, 19]</td><td>1D-(tidal) river flow model</td><td>2D-(tidal) estuary model</td><td>2D-(tidal) estuary model</td></tr>
<tr><td>Software</td><td>Mike-11</td><td>Waqua</td><td>Delft3D</td></tr>
<tr><td>Schematization</td><td>River Zeeschelde (Dender down to Dender-monde)</td><td>River Westerschelde/ (Kustzuid up to Dendermonde)</td><td>River Westerschelde/ (Zeekennis up to Dender-monde)</td></tr>
<tr><td>Use</td><td></td><td></td><td></td></tr>
<tr><td>Responsible</td><td>FH</td><td>RIKZ</td><td>WLDelft</td></tr>
<tr><td>(Orig.) Timestep</td><td>30 s</td><td>1 min</td><td>1 min</td></tr>
<tr><td>Calculation time for 1 month</td><td>1 h</td><td>1 h</td><td>1 h</td></tr>
</table>
</td></tr>
<tr><td>Actions</td><td>Software Changes
- Mike-11 is already OpenMI-compliant
- Waqua has to become OpenMI compliant
Schematization/Data Changes
- “C” has to be enlarged up to Dendermonde, where models will be linked
- Parts of “B” have to be removed
Links
- Point where models will be linked is Dendermonde.
- Bidirectional Links:
  - Flow from “A” to “B” and from “A” to “C”
  - Water level from “B” to “A” and from “C” to “A”
Scenarios</td></tr>
<tr><td>Results and Conclusions</td><td>General/conceptual/standard specific
- Results of standalone calculations of “A” and “C” deliver same results as in</td></tr>
</table>

	OpenMI configuration editor (only being linked to trigger)
	- Results of simple tests linking “A” and “C”:
	  - Place oft trigger has influence on results
	  - Linked Models can exchange data for different time steps.
	  - Time steps do not need to be a multiple of each other (small differences in resulting flow)
	  - Standalone and OpenMI coupled versions do not always deliver same results
	
	Software specific
	- Delft3D can deliver Water levels and accept Discharges, both at an up-stream boundary
	- Simple tests with prototype of Waqua’s OpenMI-version run successful [38]:
	  - Waqua can deliver water levels and accept waterlevels, discharges and velocities, both at an up-stream, open boundary
	  - RIKZ still has to continue making Waqua fully OpenMI compliant (will be ready in the very near future).
	- Extended version (of which component?) is not running in OpenMI configuration editor yet
	
	Scenario specific
	- It is expected that OpenMI communication between the models at each time step will be very time consuming [37, p. 9]

Next steps	- Perform standalone runs with model outputs as boundary conditions - Further linking of models with Omi-Ed (“A” to “C”, “A” to “B”)

B.3 Case Studies P1 to P3

B.3.1 Case Study P1: Pinios Use Case A [21]

<table>
<tr><td>Topic</td><td>Effect of advection-dispersion on sewage effluent discharge</td></tr>
<tr><td>Team</td><td>Groups “Applied Hydraulic” and “Centre of Hydrologic Information” (CHI) of the National Technical University of Athens (NTUA), Greece</td></tr>
<tr><td>Runtime</td><td>OpenMI-LIFE: 2006 – 2009</td></tr>
<tr><td>Catchment</td><td>- Upstream part of Pinios basin up to Pinios confluence with Enipeas</td></tr>
<tr><td>Motivation</td><td></td></tr>
<tr><td>Objectives</td><td>- Provide Competent Authorities with useful input for watershed planning
- Assess impact of point sources of pollution (mainly from industry and from municipal wastewater) on water quality along Pinios river.
- Study effect of dispersion and diffusion on sewage effluent from Larissa as it passes down a tributary of Pinios River
- Improve model performances</td></tr>
<tr><td>Expected Challenges</td><td>- Data availability: Different organisations collect and handle the necessary historical data using different methods
- Different time periods of available measured data exist to satisfy all models (expecially the quality model)</td></tr>
<tr><td>Models</td><td>
<table>
<tr><td>Model</td><td>A</td><td>B</td><td>C</td></tr>
<tr><td>Type</td><td>hydrologic rainfall runoff model</td><td>in-house hydraulic model</td><td>water quality model</td></tr>
<tr><td>Software</td><td>MIKE-11</td><td>RISH-1D</td><td>R-Qual</td></tr>
<tr><td>Schematization</td><td></td><td></td><td></td></tr>
<tr><td>Use</td><td></td><td></td><td></td></tr>
<tr><td>Responsible</td><td></td><td></td><td></td></tr>
<tr><td>(Orig.) Timestep</td><td>Daily, selected according to data availability</td><td>Daily, selected according to data availability</td><td>much smaller time step (for stability reasons).</td></tr>
</table>
- “A” accepts the input of rainfall and provides flow rate (m3/s) at specific locations along Pinios.
- In the case of one-direction links, “B” accepts flow rates and solves the Saint Venant equations providing time dependent stage (m) and velocity (m/sec) to “C”.
- Finally, “C” evaluates the time dependent concentration (mg/m3) at different nodes.</td></tr>
<tr><td>Needed Model Changes</td><td>- Used models are either already OpenMI-compliant or not.
- “B” had to be made OpenMI-compliant (finished) [19]</td></tr>
<tr><td>Actions</td><td>Software Changes
- R-Qual has to become OpenMI-compliant
Schematization/Data Changes
- Update, quality and consistency control of input data (rainfall and stage) [19]
- Set up “A”, “B”, and “C” and enable exchange of information between them [19, 21].
Links
- Link from “A” to “B” [19]</td></tr>
</table>

	- Link from “C” to “A” and from “C” to “B” - For starting, all interactions will be considered uni-directional. - The three models will exchange information at twenty-five nodes. At nine nodes, all three models will be linked. At seven nodes, only “B” and “C” will exchange data (point sources). **Scenarios** - Run “A” and “B” both in separate and linked modes - Test scenarios of extreme flows
Results and Conclusions	**General/conceptual/standard specific** - No significant difficulties [19] **Software specific** - RISH-1D has become OpenMI-compliant [19]. - R-Qual was modified to support needs of Pinios scenarios [19] - Migration of R-Qual expected in period Oct 2007 – Mar 2008.

B.3.2 Case Study P2: Pinios Use Case B [39, 40]

Topic	Impact of Climate Change scenarios on the reliability of a reservoir
Team	ITIA and CHI (Centre of Hydrologic Information) research group of the National Technical University of Athens (NTUA), Greece
Runtime	OpenMI-LIFE: 2006 – 2009
Catchment	- Basin upstream of the Smiokovo reservoir (maximum storage: 23,800 m3, used for water supply, irrigation, hydropower) in the northwest of Thessaly, Greece - Total area benefiting: 750 km2 - Total area of 376 km2 contributes flow to the reservoir [39] - Population: 50,000 - Agriculture is the major income source

Motivation	- Continuously reduced available water resources (e.g. unregulated groundwater pumping has lowered water table [39])
	- Increase of tourism infrastructure planned
	- Motivation for linking [40]
	  - Reservoir studies require reliable runoff data; however, historical records are usually inadequate → need to link rainfall runoff model to reservoir management model
	  - (Especially physically-based) Hydrological models are the only rational tool to assess impacts of future events on runoff regime, such as land-use, vegetation, and climate changes
	  - Reservoir simulation within hydrological models do often not account for water management aspects but only for hydraulic processes

Objectives	- Overall: Optimal design of a reservoir to satisfy the need for integrated water management in the Thessaly area
	- Study the effect of climate change in the production of hydroelectric power
	- Account for specific climate change scenarios [19]
	- Evaluate optimum operation rules [19]
	- test various scenarios using “A” and “B” in separate and linked runs and compare results
	- Assess additional effort and migration steps of making “B” compliant with OpenMI 1.4
	- Prove that OpenMI can be successfully used to assess real world problems [40]
	- Evaluate whether OpenMI can improve water resources modelling [40]
	- Assist Thessaly Competent Authorities in their decision making process [40]
	- Wider perspective [39]:
	  - Connect models created from different developers, in different languages, with different control specifications.
	  - Acquire better understanding and improve the representation and the way different processes interact in the basin
	  - Evaluate whether the simulation results have improved or not by using the OpenMI standard and under which scenarios
	  - Test the behaviour of a hypothetical scenario involving a system of 2 reservoirs in the area using bi-directional links
	- Use case specific [39]:
	  - Examine reliability of reservoir during selected calibration and validation period of three years, according to present and future demands
	  - Evaluate how different rainfall scenarios may impact the reliability of the reservoir operation

<table>
<tr><td></td><td>- Assess impact of various water allocation scenarios relatively to the different rainfall events
- Focus on specific sectors separately and investigate the possible impact of extreme events on them
- Improve regional decision making and existing policies implementations
- Prioritise and optimise possible actions taken and their expenses to secure the reliable reservoir operation</td></tr>
<tr><td>Challenges</td><td>- Time steps and time horizon of the two models
- Lack of historical flow records at critical locations (the reservior construction was recently finished in 2002)</td></tr>
<tr><td>Models</td><td>
<table>
<tr><td>Model</td><td>A</td><td>B</td></tr>
<tr><td>Type</td><td>Hydrologic Rainfall-Runoff/water basin model</td><td>in-house Reservoir management model</td></tr>
<tr><td>Software</td><td>MIKE-11 (RR/NAM module [39])</td><td>RMM-NTUA</td></tr>
<tr><td>Schematization</td><td></td><td></td></tr>
<tr><td>Use</td><td></td><td></td></tr>
<tr><td>Responsible</td><td></td><td></td></tr>
<tr><td>(Orig.) Timestep</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Actions</td><td>Software Changes
- RMM-NTUA has to be updated to become compliant with OpenMI 1.4
Schematization/Data Changes
- Set up selected models for the study area [39]
- Set up “A” for the upstream Smokovo basin to provide inflow to reservoir
- Five years of precipitation and stage data for model calibration and validation [39]
- Ensure flexibility regarding time-scale (from hourly to monthly)
Interactions/Links
- Node of information exchange between “A” and “B” is the confluence of the two streams downstream the Smokovo reservoir.
- Two more nodes will be included at areas where geometric characteristics change and assessment of parameters is needed
- Initially one-directional links, in future bi-directional links
- NAM module of “A” accepts time dependent input of rainfall and provides flow rate (m3/s) from two subbasins.
- Depending on scenarios and operational rules, the reservoir accepts estimated discharge and returns output flow rate (m3/s) to the river.
- “A” and “B” will initially share the same time step.
Scenarios
- Test various scenarios in linked and separate modes</td></tr>
<tr><td>Results and Conclusions</td><td>General/conceptual/standard specific
- No significant difficulties [19]
- The independent and linked model run results matched [40].
- “A” and “B” run independently and linked in OpenMI → OpenMI can be applied to real world scenarios [40]
Software/Model specific
- “B” was populated with data and run for different scenarios [19]
- “A” was set up to calculate rainfall runoff for a subbasin [19]</td></tr>
</table>

	Scenario specific
	- Even a relatively small-scale change in precipitation depths (+/- 10 %) affects notably the reservoir yield, as denoted through a 5-year simulation [40]
	- Further research is necessary to
	  - take into account additional components of the hydrological cycle affected by climate change, such as evapotranspiration
	  - consider representing the hydraulic components of the upstream watershed with the use of MIKE-11 [40]

Next steps	- Evaluate the use of OpenMI and real-time modelling in the operation of a system of two reservoirs supplying the same area - Examine the actual climate change scenarios and their impact to the operation of the system - Provide input to the competent authorities of the Thessaly Water District

B.3.3 Case Study P3: Pinios Use Case C [41, 42]

Topic	Lake basin restauration
Team	University of Thessaly, Greece
Runtime	OpenMI-LIFE: 2006 – 2009
Catchment	- Pinios river basin (9,500 km2) and Lake Karla Wetland basins (1,171 km2) in Thessaly region (13,500 km2), central Greece - 4,000 km2 agricultural region - Pinios water used for irrigation - Elevations from 0 to 2,800 m (mean: 500 m) - Annual precipitation from 400 mm to 1850 mm (mean: 700 mm) - Winter snowpacks in mountains - Construction of Karla reservoir (38 km2) in 2003

Motivation	- Small slope of the lake area leads to
	  - Flooding of agricultural areas,
	  - Drainage and salinity problems,
	  - Malaria. [42]
	- Problems of Lake Karla Basin:
	  - Efficient groundwater quantity and quality monitoring,
	  - Impacts of Lake Karla reservoir development on groundwater,
	  - Groundwater and surface water quality and pollution,
	  - Sustainable water resources management,
	  - Sustainable ecosystem management. [42]

Objectives	- Overall: promote integrated watershed management
	- Wider perspective:
	  - Integrated water resources planning,
	  - Flood control,
	  - Evaluation of the impact of different land use practices on water quantity and quality,
	  - Sustainable water management for irrigation and agriculture [41].
	- Use case specific: Demonstrate the linking between “A” and “B” [41]
	- Understand hydrological and ecological response to different strategies
	- Study the effect of the restoration of the Lake Karla wetlands without increasing flood risk
	- Improve evaluation of surface and groundwater resources before and after lake restoration
	- Evaluate the effect of the restauration of Lake Karla on surface and groundwater resources [19]
	- Create distributed version of UTHBAL model of Lake Karla watershed [19]
	- Couple UTHBAL and Visual Modflow models [19]
	- Test and evaluat OpenMI using the case study [19]
	- Simulate surface and groundwater resources before and after restoration of Lake Karla [42]
	- Incorporate the integrated water resources system in the OpenMI [42]
	- Define an integrated water resources simulation system in order to facilitate the study of the water balance of Lake Karla basin and the assessment of surface and groundwater resources [42]
	- Define a sustainable water resources management plan for thestudy area after the restoration of Lake Karla [42]
	- Water supply management and water demand management scenarios [42]

Challenges	- Different model discretisation: select appropirate links to exchange information - limited monitoring stations with adequate reliable data records

<table>
<tr><td>Models</td><td>

<table>
<tr><td>Model</td><td>A</td><td>B</td></tr>
<tr><td>Type</td><td>Conceptual hydrological water balance model / rainfall runoff model [41]</td><td>Groundwater model</td></tr>
<tr><td>Software</td><td>UTHBAL</td><td>Visual Modflow</td></tr>
<tr><td>Schematization</td><td></td><td></td></tr>
<tr><td>Use</td><td>Assessing surface water resources and deep infiltration</td><td>Assessing groundwater resources</td></tr>
<tr><td>Responsible</td><td></td><td></td></tr>
<tr><td>(Orig.) Timestep</td><td>Monthly</td><td></td></tr>
</table>

</td></tr>
<tr><td>Needed Model Changes</td><td>

- “B” is already OpenMI-compliant
- “A” has been adopted for assessing surface water resources and deep infiltration at monthly time scale [19]
- “A” has been migrated to .net and then to OpenMI (successful)
- “B” has been adopted for assessing the groundwater resources [19]
- Preconditions for linking models:
  - “A” and “B” have to become OpenMI-compliant,
  - Data for case studies [41]

</td></tr>
<tr><td>Actions</td><td>

Software Changes

Schematization/Data Changes
- Calibration and validation of “A” with observed runoff
- Runoff and deep infiltration time series (monthly) with “A” produced [42]
- Data for assessing surface and groundwater resources collected [19]

Links
- Model interactions:
  - The spatial domain will be set to the common part of the hydrologic and hydrogeologic watershed of the Karla catchment. The upstream part of Pinios River Basin diversion into the Karla catchment will not taken into account in the spatial domain since the abstractions of the Pinios River are predefined. The surface runoff and the infiltration to the groundwater aquifer will be calculated by “A” taking into account the given river flow in the most upstream diversion node of the Pinios River.
  - Models will exchange data on a monthly time step. [41]
- The common physical variables are :
  - river flow,
  - infiltration,
  - groundwater recharge. [41]

Scenarios
- “A” and “B” as stand-alone models [19].
- “A” has been OpenMI-linked in real-time with OpenMI-examples.
- Linking “A” and “B” for Lake Karla watershed in progress… (sept 2007) [19]
- Perform runs with “A” in order to produce model results,
- Load “A”s results as input data into “B”,
- Perform runs with “B”,
- Link models and perform new runs,
- Deal with arising issues and repeat runs [41]

</td></tr>
<tr><td>Results and Conclusions</td><td>General/conceptual/standard specific</td></tr>
</table>

	- Preliminary application and evaluation of the stand-alone models - Real-time linking in simple case studies was successful - “A” has been linked successfully in real-time with the OpenMI examples [42] **Software specific** - Difficulties in automating linking of “A” to “B”, because “B” does not offer needed component (sept 2007) [19] **Scenario specific** - Application of stand-alone models revealed: over-exploitation of groundwater aquifer in Lake Karla watershed
Next steps	- Combined application of “A” to Lake Karla watershed (On-line application of “A” and “B”) - Testing and evaluation of OpenMI structure - Adjustments of OpenMI and final evaluation - The use of the reservoir for irrigation and the repeal of many pumping wells, in addition with future scenarios, in order to estimate the hydraulic conductance between the reservoir and the groundwater aquifer and the raise of groundwater table [42]

B.4 Case Studies M1 to M3

B.4.1 Case Study M1[43]

<table>
<tr><td>Topic</td><td>Development of a new simulation-based analysis and planning methodology to identify critical water quality impacts due to combined sewer overflows (CSOs) and waste water treatment plant (WWTP) effluents in a basin wide context</td></tr>
<tr><td>Team</td><td>- Technische Universität Darmstadt / Institute of Hydraulic and Water Resources / Section of Engineering Hydrology and Water Management, Germany
- ifak e.V. Magdeburg, Germany</td></tr>
<tr><td>Funded by</td><td>- Ministry for Environment, Agriculture and Consumer Protection of the German federal state Hesse</td></tr>
<tr><td>Runtime</td><td></td></tr>
<tr><td>Catchment</td><td>- Planned:
  - entire state of Hesse (with over 700 sewer systems)
- Specific use case:
  - Upper Modau river in Hesse, Germany
  - Catchment size: 37 km2
  - partly intensively used for agriculture
  - Length of river course: 14 km
  - Retention basin at the end of the river course
  - 3 urban areas with 11 CSOs and 2 WWTPs</td></tr>
<tr><td>Motivation</td><td>- Desired quality of receiving water body not guaranteed by individual consideration of components in urban wastewater systems → integrated approach required</td></tr>
<tr><td>Objectives</td><td>- Develop of a new simulation based analysis and planning methodology and its implementation
- Create assessment tool to be used by local authorities
- Integrate already used model software
- Test the OpenMI as a concept and framework for coupling multiple existing model software packages with main focus on performance and usability</td></tr>
<tr><td>Challenges</td><td></td></tr>
<tr><td>Models</td><td>
<table>
<tr><td>Model</td><td>A</td><td>B</td><td>C</td></tr>
<tr><td>Type</td><td>Hydrological rainfall-runoff and pollution load model</td><td>Rainfall runoff and water quality model</td><td>Dynamic WWTP model</td></tr>
<tr><td>Software</td><td>SMUSI (Version 5)</td><td>BlueM (Version 0.9)</td><td>SIMBA</td></tr>
<tr><td>Schematization</td><td>Sewer system and urban catchment
A1: Brandau
A2: Emsthofen
A3: AV Modau</td><td>Modau river,
14 km length</td><td></td></tr>
<tr><td>Use</td><td></td><td></td><td></td></tr>
<tr><td>Responsible</td><td></td><td></td><td></td></tr>
<tr><td>Timestep</td><td>5 min</td><td>5 min</td><td></td></tr>
</table>
- “B” was newly developed.
- OpenMI is used in version 1.2</td></tr>
<tr><td>Actions</td><td>Software Changes
- “A” and “B” have been migrated by creating wrappers:</td></tr>
</table>

	1. Wrapper (coded in C#) which gives access to the original native Fortran-DLL from within the .NET environment. This wrapper acts as a .NET to Fortran-Adapter 2. Wrapper (coded in C#) which implements the OpenMI interface (using the methods offered by the first wrapper) **Schematization/Data Changes** **Links** - unidirectional, node-to-node links **Scenarios**

Results and Conclusions	**General/conceptual/standard specific**
	- In preliminary tests, the developed OpenMI-based integrated modelling system has proven to be a promising tool for local authorities in practice.
	- Reuse of existing datasets is a benefit for modelling integrated systems by same degree of data quality, reducing model development time
	- At least for equal time steps and unidirectional links simulation results are stable and no performance problems occured
	
	Software specific
	- Three existing model software packages were made OpenMI compliant
	- Graphical user interface showed adequate usability → acceptance of local authorities expected
	
	Scenario specific
	- The integrated system calculates plausible flows:
	  - without modelling sewer systems flows are smaller than with sewer system being modelled.
	  - modelling the sewer system results in constant additional flow from WWTP (also simulated in SMUSI) and acute impacts from CSOs

B.4.2 Case Study M2 [44]

<table>
<tr><td>Topic</td><td>Visual Decision Support System (DSS)</td></tr>
<tr><td>Team</td><td>Institute for Inland Water Management and Waste Water Treatment (RIZA), Netherlands
University of Dortmund / Institute of Environmental Research, Germany
(Both were partners in the HarmonIT project)</td></tr>
<tr><td>Runtime</td><td>HarmonIT: 2002 – 2005</td></tr>
<tr><td>Catchment</td><td>Agricultural areas in the Netherlands</td></tr>
<tr><td>Motivation</td><td>Perceived need of agricultural DSSs to gain flexibility to avoid extinction</td></tr>
<tr><td>Objectives</td><td>Simulate different scenarios, differing in land use, crop prices, drainage resistance etc.
Estimate the cost benefit ratios for each of the scenarios to find an economically optimal water management strategy
Prove that the OpenMI concept is not limited to linking models but also suited for development and control of DSSs.</td></tr>
<tr><td>Challenges</td><td></td></tr>
<tr><td>Models</td><td>
<table>
<tr><td>Model</td><td>A</td><td>B</td><td>C</td></tr>
<tr><td>Type</td><td>Groundwater model for unsaturated zone</td><td>Agricultural and economic model</td><td>simple Decision Support System</td></tr>
<tr><td>Software</td><td>Mozart</td><td>Agricom</td><td>AM-DSS (Agricom Mozart Decision Support System)</td></tr>
<tr><td>Schematization</td><td></td><td></td><td></td></tr>
<tr><td>Use</td><td></td><td></td><td></td></tr>
<tr><td>Responsible</td><td></td><td></td><td></td></tr>
<tr><td>Timestep</td><td></td><td></td><td></td></tr>
</table>
“C” comprises a linked system of “A” and “B” and is itself OpenMI compliant.
</td></tr>
<tr><td>Actions</td><td>Software Changes
The AM-DSS-component “C” which uses “A” and “B” via OpenMI, has been newly developed within the HarmonIT project. It is an OpenMI compliant component itself.
Schematization/Data Changes
Links/Data Exchange
Within the component “C” data exchange between “A” and “B” is realized.
“C” as OpenMI-compliant module itself exchanges data with “A” and “B” in bidirectional manner</td></tr>
<tr><td>Results and Conclusions</td><td>General/conceptual/standard specific
OpenMI has proven to be flexible and adequate enough to be used in DSS development.
OpenMI is not a framework but enables components to directly communicate with each other by means of the OpenMI interfaces
Software specific
OpenMI compliant DSS enables to make pre-defined scenario computations and present results to user
Developing applications like AM-DSS is not a big effort, especially if model</td></tr>
</table>

	components provide all necessary items and a graphical user interface which can be reused - Mozart and Agricom still have a limited number of exchange items which prevents development of sophisticated DSS **Scenario specific** - It is possible to develop a DSS using OpenMI interfaces and software - Being OpenMI compliant is not enough to ensure full implementation of a component in a DSS: the availability of input- and output exchange items determines the applicability of components - The controller function of OpenMI based DSS will be much simpler as in “hard-wired” systems, as much bookkeeping is kept by the underlying model components, especially if all input and output can be done through interfaces

B.4.3 Case Study M3 [45, 46]

Topic	Relatively large-scale application of the OpenMI
Team	- WRc plc, UK - Wallingford Software Ltd, UK - WL/Delft Hydraulics, NL - DHI Water and Environment, Denmark
Runtime	

Catchment	- Simple artificial catchment, constructed for demonstration purpose
	- River system with
	  - runoff,
	  - sewer systems and sewage works, directly connected to a lake,
	  - sewer spill point to a river feeding the lake
	  - the lake discharging at one end to a further river reach

Motivation	-

Objectives	- Demonstrate
	  - that a complex model integrating many programs can be constructed
	  - the applicability of the OpenMI by means of a constructed problem of integrated modelling

Challenges	- Different flow units, different water quality parameters - Many of the programs hav not been coupled in the past - Ensure that consistent information is passed between programs (especially for water quality, where organic matter is represented as COD or BOD and different fractionating approaches are used)
Models	(see table below)

				linked to							
	Model software	Model type	Time step	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
A	SOBEK-RR (Rural-RR)	Rainfall Runoff	10 min		x						x
B	SOBEK-CF (River 1DFlow)	Channel Flow	10 min					x			
C	SOBEK-SF (Urban 1DFlow)	Sewer Flow	1 min		x						
D	Hymos Database	Rainfall		x							
E	InfoWorks RS	Channel Flow	20 s / 5s (WQ)		x						x x
F	InfoWorks CS	Sewer Flow	1 min					x		x x	
G	STOAT	WWTP	1 min					x			x
H	SULIS	Lake	2 s					x x			

Actions	-
Results and Conclusions	**General** - OpenMI can handle many data transformations without explicit user intervention - OpenMI has facilitated linking many disparate water-cycle programs

	- OpenMI provides feasible solution for the IT communication problem - The OpenMI technology is not sufficient by itself. The different skills available through different modelling areas must cooperate in ensuring that the different programs connect in the right manner - Quantities can be manipulated at the OpenMI level for simple one-to-one ralationships (e.g. unit conversion). - Contrary, many-to-one relationships (e.g. suspended solids in the target program is the sum of several solids fractions in the source) require support by the programs itself - No unified reporting mechanism but new OpenMI compliant programs will solve this problem - As OpenMI is not an integrated software suite, the conceptional overhead is low. Each program is manipulated individually - The results of the catchment model being run have to be analyzed through the individual user interfaces of the various model applications incorporated - OpenMI allows larger problems to be tackled, but does not remove the constraints of ensuring communication between the different technical work areas in understanding the total output - OpenMI has provided a social framework to encourage individual teams to work together to provide better modelling data for the decision makers **Software specific** - Model developers still have to communicate about semantics of exchanged items (e.g. BOD/COD) and locations - The simple approach currently used in the OpenMI demonstrator enhances understanding of the inter-relationships between the different programs **Scenario specific** - The programs have been successfully run coupled together - Computation time of whole model did not increase considerably, but slow-down was caused by need to run the simulation at a small timestep. - Additional overhead caused by data exchange between the different programs but this was present at the Windows level and is intrinsic to the program communication procedures adapted by the Windows operating system, rather than to those imposed by the OpenMI itself.

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