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Integrating knowledge to assess coastal vulnerability to sea-level rise: The development of the DIVA tool

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ABSTRACT

This paper describes the development of the DIVA tool, a user-friendly tool for assessing coastal vulnerability from subnational to global levels. The development involved the two major challenges of integrating knowledge in the form of data, scenarios and models from various natural, social and engineering science disciplines and making this integrated knowledge accessible to a broad community of end-users. These challenges were addressed by (i) creating and applying the DIVA method, an iterative, modular method for developing integrating models amongst distributed partners and (ii) making the data, scenarios and integrated model, equipped with a powerful graphical user interface, directly and freely available to end-users.

1. Introduction

Knowledge on coastal vulnerability enables scientists and policymakers to anticipate impacts that could emerge as a result of sea-level rise and other effects of climate change. It can thus help to prioritize management efforts that need to be undertaken to minimize risks or to mitigate possible consequences. In view of the high natural and socio-economic values that might be threatened or lost in coastal zones (Nicholls et al., 2007), it is therefore important to identify the types and magnitude of problems that different coastal areas may have to face, as well as possible solutions.

Global vulnerability assessments carried out by Hoozemans et al. (1993) and Baarse (1995) suggest that some 189 million people presently live below the once-per-1000-years storm-surge level. They estimate that, under current conditions, an average of 46 million people per year experience storm-surge flooding. Hoozemans et al. (1993) estimate that this number would rise to over 100 million people per year, assuming 1 m of sea-level rise and 30 years of socio-economic development. The assessment also projects that, under the same scenario, 59% of coastal wetlands will be lost.

These global vulnerability assessments played a central part in the preparation of the World Coast Conference 1993 and several IPCC reports. They have also been used extensively for further academic analyses, including integrated assessment modelling. However, with the widespread use of the global assessments, their limitations have become increasingly apparent. These limitations include the following:

- The obsolescence and low spatial resolution of underlying data sources;
- the limited number of scenarios used;
- the reliance of global mean sea-level rise as the only driver of coastal vulnerability;
- the non-consideration of bio-geophysical and socio-economic dynamics and feedback;
- arbitrary and rather simplistic assumptions regarding adaptation.

To address these limitations and thus provide updated policy-relevant information on coastal vulnerability involves two major challenges. First, knowledge in the form of data, scenarios and models from different natural, social and engineering science disciplines needs to be integrated in a much more comprehensive way than had ever been done for coastal vulnerability. This is particularly true for the feedbacks between natural and social systems, as well as including adaptation. Second, the integrated knowledge must be made available in a form that allows a diverse community of end-users and policy-makers to answer the specific questions they are confronted with.

This paper presents the systematic approach by which the EU-funded project DINAS-COAST (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Sea-Level Rise) has addressed these challenges. The project developed an innovative, modular and iterative approach for integrating knowledge about coastal subsystems. This

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approach was then applied to produce the tool called DIVA (Dynamic and Interactive Vulnerability Assessment), a dynamic, interactive and flexible software tool that enables its users to produce quantitative information on a range of coastal vulnerability indicators, for user-selected climatic and socio-economic scenarios and adaptation strategies, on national, regional and global scales, covering all coastal nations. DIVA 1.5.5 was released on a CD-ROM in 2006 (DINAS-COAST Consortium, 2006) and is freely available for download from http://www.pik-potsdam.de/diva.

The purpose of this paper is not to give a full description of the integrated model itself. Rather the purpose is to present the process by which the integrated model was developed. In so doing, we hope to contribute to the methodological advancement of transdisciplinary, integrative science by providing the rapidly growing number of researchers active in this field with insights and tools that would enable many to tackle similar challenges. A detailed account of the integrated model can be found in the technical documentation that comes along with the tool (DINAS-COAST Consortium, 2006) and the academic literature (Hinkel, 2005; Hamilton et al., 2005; Brander et al., 2006; Vafeidis et al., 2006; Hinkel and Klein, 2007; McFadden et al., 2007a,b; Vafeidis et al., 2008).

The remainder of the paper is organized as follows. Section 2 presents a brief overview of the evolution of methodologies applied for assessing the vulnerability of coastal zones to sea-level rise. Section 3 analyses the requirements that resulted from the two challenges outlined above. Section 4 then presents the method designed to address these challenges, that is, the method applied to develop the DIVA tool. Section 5 presents the tool's structure and components. Section 6 briefly presents some results of DIVA and compares these with results obtained by Hoozemans et al. (1993) and Baarse (1995). Section 7 discusses lessons learned in developing DIVA, and their significance to transdisciplinary science in general, and to vulnerability assessment in particular. Finally, Section 8 presents conclusions and proposes activities for future work.

2. Evolution of methodologies for assessing coastal vulnerability to sea-level rise

Before climate change emerged as an academic focus, vulnerability as such was not an important concept in coastal research. Traditionally, research in coastal zones has been conducted mainly by geologists, ecologists and engineers, roughly as follows (Klein, 2002):

- Geologists study coastal sedimentation patterns and the consequent dynamic processes of erosion and accretion over different spatial and temporal scales;
- ecologists study the occurrence, diversity and functioning of coastal flora and fauna from the species to the ecosystem level;
- engineers take a risk-based approach, assessing the probability of occurrence of storm surges and other extreme events that could jeopardize the integrity of the coast and the safety of coastal communities.

The challenge of climate change has spurred the collaboration between these three groups of coastal scientists; vulnerability has become the integrating focus of this research collaboration. Since 1990 a number of major efforts have been made to develop guidelines and methodologies to assess coastal vulnerability, which combined the expertise of the three disciplines and of economics. In 1992, the former Coastal Zone Management Subgroup of the IPCC published the latest version of its Common Methodology for Assessing the Vulnerability of Coastal Areas to Sea-Level Rise (IPCC CZMS, 1992). It comprises seven consecutive analytical steps that allow for the identification of populations and physical and natural resources at risk, and of the costs and feasibility of possible responses to adverse impacts.

The Common Methodology has been used as the basis of assessments in at least 46 countries; quantitative results were produced in 22 country case studies and eight subnational studies (for an overview see Nicholls, 1995). The aforementioned assessments by Hoozemans et al. (1993) and Baarse (1995) applied the Common Methodology on a global scale. Studies using the Common Methodology were meant to serve as preparatory assessments, identifying priority regions and priority sectors and providing an initial screening of the feasibility and effect of coastal protection measures. At most, seven impact indicators were considered, as follows (IPCC CZMS, 1992):

1. People affected (the people living in the coastal floodplain that are affected by sea-level rise);
2. people at risk (the average annual number of people flooded by storm surge);
3. capital value at loss (the market value of infrastructure which could be lost due to sea-level rise);
4. land at loss (the area of land that would be lost due to sea-level rise);
5. wetland at loss (the area of wetland that would be lost due to sea-level rise);
6. potential adaptation costs, with an overwhelming emphasis on protection;
7. people at risk, assuming the adaptation considered in indicator 6.

The studies using the Common Methodology have been successful in raising awareness of the potential magnitude of climate change and its possible consequences in coastal zones. They thus provided a motivation for implementing policies and measures to control greenhouse gas emissions. In addition, they encouraged long-term thinking and triggered more detailed local coastal studies in areas identified as particularly vulnerable, the results of which would contribute to coastal planning and management (Klein and Nicholls, 1998; Klein, 2002).

Nonetheless, a number of problems have been identified with the Common Methodology, which mainly concern its data intensity and its simplified approach to bio-geophysical and socio-economic system response (Klein and Nicholls, 1999). In response to these problems, alternative assessment methodologies have been proposed, but they have generally not been applied by anyone other than their developers. A semi-quantitative methodology proposed by Kay and Hay (1993) was applied in a number of South Pacific island countries, where it was felt that the Common Methodology put too much emphasis on economic impacts. An index-based approach proposed by Gornitz et al. (1994) included the risk of hurricanes and was developed for use along the east coast of the United States. However, it did not consider socio-economic factors.

In 1994 the IPCC published its Technical Guidelines for Assessing Climate Change Impacts and Adaptations (Carter et al., 1994), which provide system-independent guidance to countries that wish to assess their vulnerability to climate change. The Technical Guidelines are outlined in a similar fashion to the Common Methodology, but fewer analytical steps are implied and less prior knowledge is assumed. In addition, the Technical Guidelines are not prescriptive in the choice of scenarios, tools and techniques to conduct the analysis. For a range of socio-economic and physiographic systems, the United Nations Environment Programme (UNEP) Handbook on Methods for Climate Change Impact Assessments and Adaptation Strategies (Feenstra et al., 1998) offers a detailed elaboration of the IPCC Technical

Guidelines, including for coastal zones (Klein and Nicholls, 1998). The UNEP Handbook has been used in a range of developing countries under the UNEP Country Studies Programme and the first phase of the Netherlands Climate Change Studies Assistance Programme. The United States Country Studies Program used similar guidance provided by Benioff et al. (1996).

In the late 1990s, the EU-funded project SURVAS (Synthesis and Upscaling of Sea-Level Rise Vulnerability Assessment Studies) aimed to synthesize and upscale all available coastal vulnerability studies and to develop standardized data sets for coastal impact indicators suitable for regional and global analysis (de la Vega-Leinert et al., 2000a, 2000b; see also http://www.survas.mdx.ac.uk/). However, this effort was only partially successful: synthesis and upscaling was impeded by the fact that studies had used different methodologies, scenarios and assumptions. As a result, the global assessments by Hoozemans et al. (1993) and its update by Baarse (1995) remained the only sources of global information on coastal vulnerability to sea-level rise.

3. Requirement analysis

DIVA has been developed to meet the demand for new information on coastal vulnerability on a global scale, addressing important limitations of the earlier global studies listed in the previous section. Important improvements are the inclusion of feedbacks within the combined natural and socio-economic coastal system and the more explicit and realistic representation of adaptation (see Section 5).

To make these improvements required integrating natural and social science knowledge in a much more comprehensive way than had ever been done for coastal vulnerability assessment. No single scientific discipline, scholar or research institute could have developed DIVA independently. Each project consortium member provided unique knowledge about a specific coastal subsystem in the form of scenarios, data, models and relevant questions to be addressed. Incompatible conceptualizations (or terminologies) had to be harmonized and different model types (e.g., discrete, continuous and optimization models) had to be incorporated.

Integration was complicated by the fact that project partners were distributed over various institutes. As a result, frequent project meetings were not possible, and most of the model development was coordinated using e-mail, the Internet, and telephone calls. These constraints called for a modular approach, in which the individual project partners can represent and validate their subsystem knowledge in the form of self-contained modules.

Model integration involved a further challenge: it was not possible to define the interfaces between the modules at the beginning of the project. As is frequently the case in integrative research, the interactions between the various subsystems were not fully understood at the start of the project; instead, such understanding typically develops during the project and becomes a major result of the project itself. Furthermore, the development of the model had to take place simultaneously with the development of an appropriate database, because no existing database was suitable for use in DIVA.

Taking into account that scientific data and models about coastal phenomena themselves are changing quickly, a further aim was to create a tool that can be easily upgraded as new knowledge becomes available.

A second set of requirements comes from the end-user's perspective. The goal of DINAS-COAST was not only to integrate knowledge but also to make available this knowledge to a wider audience. From having been involved in previous coastal vulnerability assessments, the project consortium members were aware that many different end-users are interested in coastal vulnerability, including academics, non-governmental organizations (NGOs), government analysts, and United Nations and other international organizations, all of which, however, have specific questions. Hence, a multitude of scenarios, adaptation options, impact indicators and spatial scales need to be considered in a global vulnerability assessment, which means that vast amounts of data can be produced. To publish and make available only a limited number of model runs would therefore be a strong limitation to users. By making available the model itself, users can instead explore those questions in which they are interested.

To this end, a graphical user interface (GUI) is required that reflects the specific information needs of the users. The GUI must be intuitive and user-friendly, but also allow for advanced interactions for more professional users. At the basic level, users must be able to select climate and economic scenarios, choose from a set of adaptation strategies, run the model and analyze the results. A question frequently asked by policy makers is which country or region is more or most vulnerable, so the GUI puts special emphasis on enabling comparative analyses of impacts under different scenarios and for adaptation strategies. At the advanced level, users should also be able to edit the data, use their own scenarios and possibly even alter the model's algorithms. The GUI should provide import and export facilities for standard Office and GIS applications. Finally, making the model available for user interaction requires a fast model.

Both sets of requirements necessitate a flexible tool in the sense that it is possible to make changes to data, algorithms, subsystem interactions and the GUI during its development phase. But how does one design a product that is a moving target? The answer for DINAS-COAST was that rather than designing the product (i.e. the DIVA tool), it designed the process of developing the product. Instead of providing a rigid specification of the final product at the outset of the project, DINAS-COAST created a method, called the DIVA method, which organizes and facilitates the tool development process, and allows for the iterative refinement of the tool. The actual DIVA tool has been built using the DIVA method. While the DIVA tool is specific to DINAS-COAST, the DIVA method is generic and could easily be reused in other contexts with similar requirements. The next two sections present the DIVA method and the DIVA tool, respectively.

4. The DIVA method

The DIVA method is a method for building modular integrated computer models by distributed partners. It was developed to address the aforementioned challenge of supporting the process of integrating knowledge.

The DIVA method consists of two parts: a modelling framework and a semi-automated development process. The modelling framework frames the model to be built by providing a general a priori conceptualization of the system to be modelled; only those phenomena that can be expressed using the framework's concepts can in fact be modelled. The development process facilitates integration on the process level. It frames the iterative specializing of the framework's general concepts to the needs of the specific problem addressed. For a more technical presentation of the DIVA method see Hinkel (2005).

The modelling framework provides concepts for expressing static information about the system, as well as concepts for representing the system's dynamics. The statics of the system are represented by a data model consisting of geographic features, properties, and relations, which follows the OpenGIS Abstract Specification of the Open GIS Consortium (http://www.opengis.org/techno/abstract.htm). The geographic features represent the real-world entities such as regions, countries and river basins. Properties capture the quantitative information about the features.

For example, a country might have the property "area" or a river the property "length". Finally, relations describe how the features are structured. For example, the feature "region" might contain several "country" features. The dynamics of the system are represented in the form of first-order difference equations. For example, the surface area of coastal wetlands in a country might be a function of the wetland surface area in the previous time step and of the value of the sea-level scenario driving the model in the current time step.

The development process organizes the integration of knowledge, based on the a priori conceptualization provided by the modelling framework. Knowledge about the system enters the process in four ways (see Fig. 1):

1. The ontology, which is a shared language to talk about the system to be modelled;
2. the algorithms, which represent the system's dynamics;
3. the data, which represent the initial (observed) state of the system and the scenarios that represent the system's possible future evolutions;
4. the use-cases, which specify how the user can interact with the model via the GUI.

The first task of any iteration of the development process is the elaboration of the shared ontology. An ontology is a specification of a conceptualization (Gruber, 1993), that is a list of terms and their definitions. Elaborating a shared ontology means, in the case considered here, that the geographic features, properties and relations that constitute the modelled system must be specified. According to the role they have in the system's dynamics, all properties of the features must be classified into one of four categories: driver, state variable, diagnostic variable and parameter. For example, the country's area is static (a parameter), while its population might be a driver. The development of the ontology is a joint responsibility of the entire project consortium and forms the basis for all discussions about the system. The ontology is stored in a central repository as an XML (extensible markup language) document.

Once the knowledge has entered the development process, most subsequent processes are automated and model development proceeds in three parallel tracks: the database development, the GUI development and the algorithm development. The ontology feeds into all three tracks. The database development consists of two steps. First, raw data must be preprocessed to fit the ontology. Second, the preprocessed data is automatically converted into the DIVA database format (Vafeidis et al., 2008). The GUI is automatically generated using the XML document, which also includes a description of the properties, the units, the minimum and maximum values, and so on.

The ontology is also used to generate automatically Java source code, which is then used by the project partners to code the algorithms. The model's ontology is then hard-coded in Java, which means that an algorithm will only compile if it is consistent with the ontology. Related algorithms are grouped into modules. For example, a project partner could write a module called CountryDynamics, which simulates how the properties of the feature "country" evolve over time. Before a module is submitted for inclusion into the integrated model it is run and validated in stand-alone mode.

The last step of any iteration of the development process involves the analysis of the modules and their linkages, and the validation of the complete model. Whenever a new version of a module is submitted, the project's internal tool development website is automatically updated, offering documentation and the new integrated model for download. An important document that is automatically generated is a graph that visualizes the flow of data through the modules (see Fig. 2). Module developers can use this graph to analyze the interactions between the modules and decide whether any changes need to be made in the next iteration of the development process. This may then create the need to update the ontology, change the algorithms, incorporate new data, and adjust the GUI's functionality.

The principal advantage of this iterative approach to model development is that the interfaces between the subsystems modules do not have to be specified before the coding can start. The module developers can start coding their knowledge before analyzing which information they need to take from and provide to other modules. The development process can be iterated as many times as necessary. At any stage new knowledge in the form of data, algorithms or linkages between the modules can be incorporated, yet there is always a complete model available.

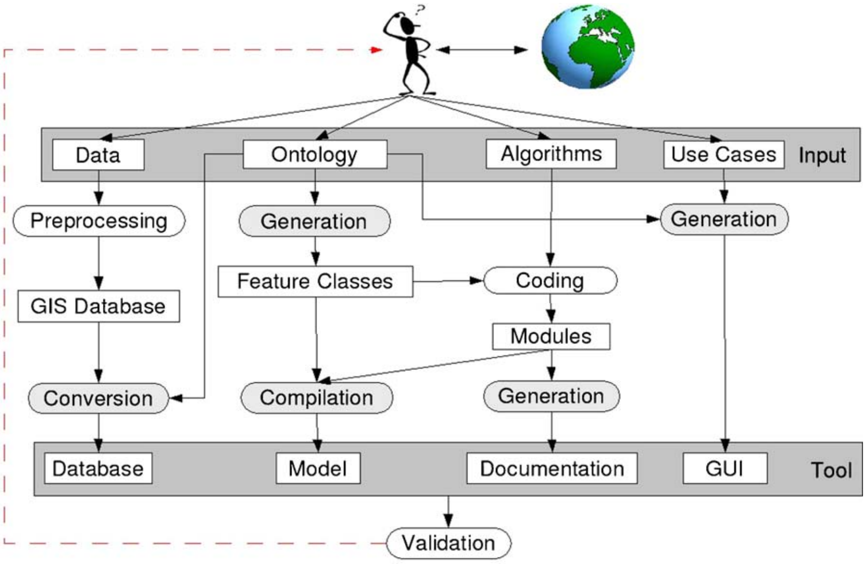


Fig. 1. The DIVA development process. Boxes denote deliverables, ovals denote processes, and shaded ovals denote automated processes (GUI stands for graphical user interface).

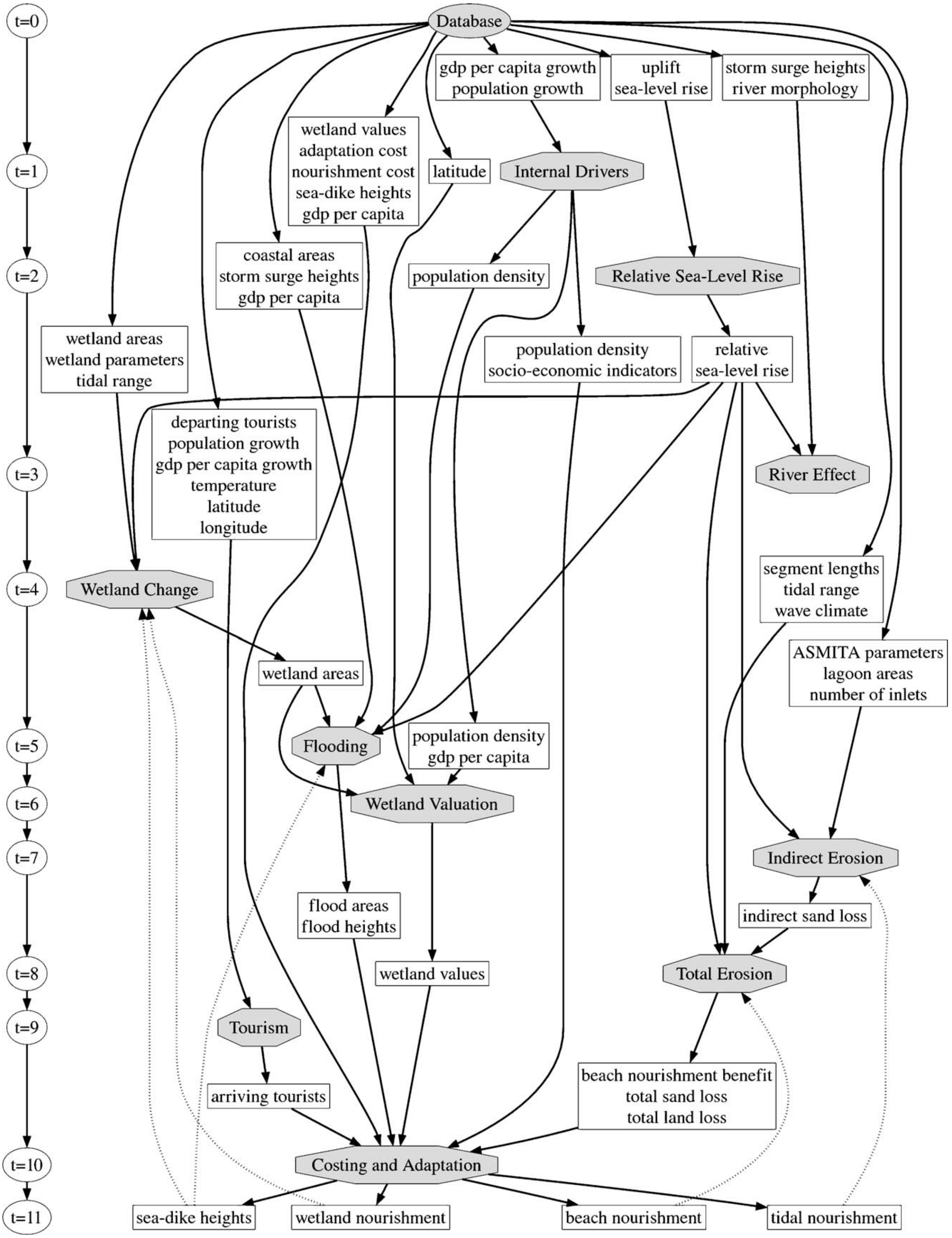


Fig. 2. Module linkages in DIVA 2.0.3. Octagons represent the modules, rectangles represent data, the solid arrows represent the flow of data during one time step, and the dotted arrows represent the data fed into the next time step.

5. The DIVA tool

5.1. Components

The DIVA method described above was applied to develop the DIVA tool. The DIVA tool comprises four main components:

1. A detailed global database with biophysical and socio-economic coastal data;
2. global and regionalized sea-level and socio-economic scenarios until the year 2100;
3. an integrated model, consisting of interacting modules that assess biophysical and socio-economic impacts and the potential effects and costs of adaptation;
4. a graphical user interface for selecting data and scenarios, running model simulations and analyzing the results.

The database contains information on roughly 80 biophysical and socio-economic parameters of the world's coats. Data is represented on the basis of seven different types of geographic features (DIVA's ontology, see Section 4): coastline segments, administrative units, countries, rivers, tidal basins, world heritage sites and 5 × 5 degree grid cells. Most data is attributed to the coastline segments. These coastline segments were developed by decomposing the world's coastline, based on its biophysical and socio-economic characteristics, into 12,148 variable-sized segments that are homogeneous in terms of impacts and vulnerability to sea-level rise (McFadden et al., 2007a). The choice to represent data this way was motivated by the requirement to have a fast model. Attributing the information to the one-dimensional coastline simplifies the calculations of the model because all expensive GIS operations have already been performed as part of the data preprocessing (Hinkel, 2005; Vafeidis et al., 2006, 2008).

The scenarios that drive the model contain information about sea-level rise, land-use change and socio-economic development (i.e. population and economic growth), all of which was derived from the scenarios of the IPCC Special Report on Emission Scenarios (SRES; Nakicenovic and Swart, 2000). The sea-level scenarios were produced with the climate model of intermediate complexity CLIMBER-2 of the Potsdam Institute for Climate Impact Research in Germany (Petoukhov et al., 2000). For each SRES emission scenario six different sea-level scenarios, assuming three different climate sensitivities, as well as uniform and regionalized sea-level rise, were produced.

The integrated model of the DIVA tool consists of a number of modules, developed by the various project partners and representing the coastal subsystems. The model computes the impacts of sea-level rise on natural and human systems, as well as the effects of human adaptation on these impacts. Table 1 lists all modules and Fig. 2 shows the flow of data through the modules. Section 5.2 discusses the integrated model in more detail.

The graphical user interface (GUI) of the DIVA tool enables its user to choose scenarios and adaptation strategies, to run the model, and to analyze and compare the results for different regions, time steps, scenarios and adaptation strategies. The GUI was built on the basis of the Delft Tools (http://www.demis.nl/home/pages/products.htm), which is a collection of software components for decision support and temporal-spatial data analysis. Input and output data can be visualized in the form of tables, graphs, charts, and maps. All data used by the model can be edited, imported from spreadsheets or exported to standard Office formats. Fig. 3 is a screen shot of the GUI of DIVA, showing the total adaptation costs per country.

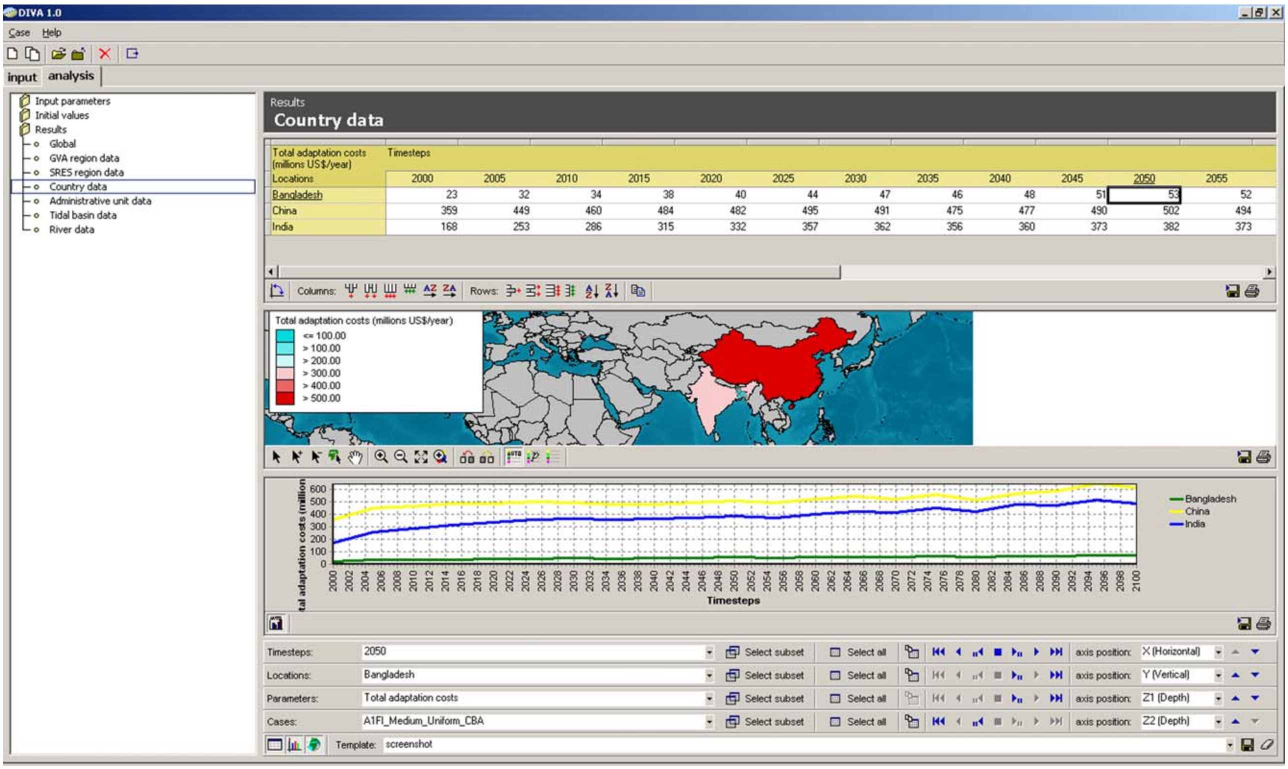
5.2. The integrated model

The integrated DIVA model first produces relative sea-level scenarios by combining the sea-level scenarios from CLIMBER-2 with the vertical land movement. The latter is a combination of glacial-isostatic adjustment according to the geo-physical model of Peltier (2001) and, following McGill (1958), a uniform 2 mm/year subsidence in deltas. Human-induced subsidence (due to ground fluid abstraction or drainage) is not considered due to the lack of consistent data.

With the relative sea-level scenarios as input, four types of biophysical impacts are assessed: land loss, flooding, salinity intrusion in river deltas and estuaries, and wetland change. Land is lost due to submergence and coastal erosion. Both direct and indirect coastal erosion are considered. The direct effect of sea-level rise on coastal erosion is estimated using the Bruun rule (Zhang et al., 2004; Nicholls, 2002). Sea-level rise also affects coastal erosion indirectly as tidal basins become sediment sinks under rising sea level, trapping sediments from the nearby open coast into tidal basins. This indirect erosion is calculated using a simplified version of the ASMITA model (Aggregated Scale

Table 1
The modules in DIVA 2.0.3.

Module name	Author(s)	Description
Relative sea-level rise	Robert Nicholls, Loraine McFadden	Creates relative sea-level rise scenarios by adding vertical land movement to the climate-induced sea-level rise scenarios.
River effect	Rob Maaten	Calculates the distance from the river mouth over which variations in sea level are noticeable.
Indirect erosion	Luc Bijsterbosch, Zheng Bing Wang, Gerben Boot	Calculates the loss of land, the loss of sand and the demand for nourishment due to indirect erosion in tidal basins. This is a reduced version of the Delft Hydraulics ASMITA model (Stive et al., 1998).
Total erosion	Robert Nicholls, Loraine McFadden	Calculates direct erosion on the open coast based on the Bruun rule. Sums up direct erosion and indirect erosion for the open coast, including the effects of nourishment where applied.
Wetland change	Loraine McFadden, Robert Nicholls, Tom Spencer, Jochen Hinkel	Calculates area change due to sea-level rise, sea dike construction and possible wetland nourishment for six types of wetlands.
Flooding	Robert Nicholls, Richard Tol, Jochen Hinkel	Calculates flooding due to sea-level rise and storm surges, taking into account sea dikes.
Wetland valuation	Luke Brander, Onno Kuik, Jan Vermaat	Calculates the value of different wetland types as a function of GDP, population density and wetland area.
Tourism	Jacqueline Hamilton, David Maddison, Richard Tol	Calculates number of tourists per country.
Costing and adaptation	Richard Tol, Gerben Boot, Poul Grashoff, Jacqueline Hamilton, Oliver Hansen, Jochen Hinkel, Maren Lau, Loraine McFadden, Robert Nicholls, Christine Schleupner	Calculates socio-economic impacts of the geodynamic effects, taking into account preset and/or user-defined adaptation options.



Total adaptation costs (millions US$/year)	Timesteps											
Locations	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055
Bangladesh	23	32	34	38	40	44	47	46	48	51	53	52
China	359	449	460	484	482	495	491	475	477	490	502	494
India	168	253	286	315	332	357	362	356	360	373	382	373

Timesteps: 2050 — axis position: X (Horizontal)
Locations: Bangladesh — axis position: Y (Vertical)
Parameters: Total adaptation costs — axis position: Z1 (Depth)
Cases: A1FI_Medium_Uniform_CBA — axis position: Z2 (Depth)
Template: screenshot

Fig. 3. A screen shot of the graphical user interface of the DIVA tool.

Morphological Interaction between a Tidal basin and the Adjacent coast; Stive et al., 1998; Van Goor et al., 2003). About 200 tidal basins around the world are considered. DIVA includes beach and tidal nourishment, that is, the replacement of eroded sand, as adaptation options.

The flooding of the coastal zone caused by sea-level rise and associated storm surges is assessed for both sea and river floods. Taking into account the effects of dikes, flood areas for return periods from 1-in-1 to 1-in-1000 years are computed. Due to the difficulties of predicting changes in storm surge characteristics (e.g., von Storch and Woth, 2008), the present storm surge characteristics are simply displaced upwards with the rising sea level. The adaptation option considered is building higher dikes.

The salinity intrusion into the aquifers of river deltas and estuaries is assessed for about 200 major rivers. Based on Schijf and Schönfeld (1953), the length of salt water intrusion into the river and the land area affected by salinity are calculated, using relative sea-level rise and storm surge characteristics as input (see also Maaten, 2006). No adaptation options are considered. DIVA does not account for salinity intrusion into coastal aquifers.

The change in coastal wetlands is assessed in terms of wetland area and composition of wetland vegetation types. Wetlands respond to sea-level rise by horizontal inland migration, vertical elevation change and transitions to other wetland types (Nicholls et al., 1999). The response is a function of the relation of relative sea-level rise to tidal range, sediment supply and migration space. The latter is, in turn, negatively influenced by the building of sea-dikes. Six different wetland types are considered: coastal forest, high unvegetated wetland, low unvegetated wetland, freshwater marsh, saltmarsh and mangroves. The adaptation option included is wetland nourishment. See McFadden and Hinkel (2006) and McFadden et al. (2007b) for more detail.

DIVA also assesses the social and economic consequences of the physical impacts described above, taking into account socio-economic scenarios. Social consequences or impacts are expressed by three indicators. The coastal floodplain population gives the number of people that live below the 1000-year storm-surge level. The indicator people actually flooded gives the expected number of people subject to annual flooding. The indicator forced migration gives the number of people that have to migrate from land that would be permanently lost due to erosion and submergence. For the calculation of these numbers the gridded population of the world has been used (CIESIN and CIAT, 2004).

The economic consequences are expressed in terms of damage costs and adaptation costs. For the calculation of damage costs, the above biophysical and social impacts have been valued. The cost of land loss is calculated based on the assumption that all land lost was used for agriculture. Agricultural land has the lowest value and it is assumed that if land used for other, higher-valued purposes (e.g., industry or housing) is lost, then those uses would move and occupy agricultural land. The cost of salinity intrusion into river deltas and estuaries is calculated in terms of the agricultural land affected and the assumption that saline agricultural land has half the value of non-saline land. The cost of floods is calculated as the expected value of damage caused by sea and river floods based on land-use and a damage function logistic in flood depth. The costs of wetland change are calculated based on a value transfer function derived from a global meta-analysis of wetland valuation literature (Brander et al., 2006). The cost of migration is calculated on the basis of loss of GDP per capita. For a detailed account of the valuation of impacts see Tol (2006).

Adaptation costs are calculated for all of the above adaptation options (i.e. dike building, beach nourishment, tidal nourishment and wetland nourishment; no adaptation option is considered for salinity intrusion). Dike costs are taken from Hoozemans et al. (1993). The costs of beach, tidal and wetlands nourishment were

Table 2
The output of DIVA 2.0.3.

Impact	Output Variable
Erosion	Sand lost, land lost, people forced to migrate, cost of land loss, cost of migration, cost of beach and tidal nourishment
Flooding	Coastal floodplain population, people actually flooded, cost of flooding, dike height, cost of dike building
Wetland change	Area of different types of wetlands, monetary value of wetlands, wetland area lost, cost of wetland loss, cost of wetland nourishment
Salinity intrusion	Length of river affected by salinity intrusion, land area influenced by salinity intrusion, cost of salinity intrusion

derived from expert consultation. Different cost classes are applied, depending on how far away the sand for nourishment is found.

DIVA implements the adaptation options according to various complementary adaptation strategies. When running DIVA, an adaptation strategy has to be selected for each of the four adaptation options (i.e. beach, tidal and wetland nourishment and dike building). The simplest strategy is ‘no adaptation’, in which DIVA only computes potential impacts. For beach, tidal and wetland nourishment, there is a ‘full protection’ strategy, according to which DIVA nourishes beaches, tidal basins and wetlands as much as needed in order to preserve the status quo. For dike building, the equivalent strategy is the ‘constant protection’ strategy, according to which DIVA raises dikes such that a predefined protection level, i.e. a flood return period against which to protect, is kept. Finally, the ‘cost-benefit adaptation’ strategy balances costs and benefits of adaptation. For sea-dike building, for example, this strategy maintains an optimal protection level or dike height throughout time (Tol, 2006).

Note that the DIVA tool is not explicit about the exact meaning of vulnerability. This is done for two reasons. First, there is no accepted definition of vulnerability, or a single way of making it operational (e.g., Brooks, 2003; O’Brien et al., 2004; Adger, 2006; Eakin and Luers, 2006; Füssel and Klein, 2006). Second, we view vulnerability as having a strong subjective dimension, that is, statements about vulnerability depend on personal preferences (Ionescu et al., 2009). The model’s output has many components that are not objectively comparable (see Table 2) and therefore unsuitable for aggregation into a single measure. Only the monetary components of the output can be readily compared and added up, which is the basis for the above-mentioned ‘cost–benefit’ adaptation strategy. Hence, DIVA does not produce a single measure or index of vulnerability. The comparison of the various components of the output is left to the user’s own judgement.

6. DIVA tool application

This section presents selected results of the DIVA tool[1] and discusses these against the background of the previous global vulnerability assessment carried out by Hoozemans et al. (1993). Note that the numbers produced by the two studies cannot be compared directly because the scenarios and definitions of impact indicators are different. The purpose of jointly presenting these results is to illustrate the improvements introduced by the DIVA tool.

Both Hoozemans et al. (1993) and DIVA estimated the floodplain population (i.e. the number of people living below the once-per-1000-years storm-surge level) and the expected number of people subject to annual flooding (called ‘people at risk’ in the former and ‘people actually flooded’ in the later assessment). Table 3 shows results of the two assessments for these two indicators. For each assessment, one scenario with and one without adaptation is presented. The numbers are, however, difficult to compare, because of the different assumptions made. Hoozemans et al. (1993) assumed 1 m of sea-level rise together with 30 years of socio-economic development relative to 1990 (thereby only considering population growth). The results produced by DIVA are based on a consistent combination of sea-level rise and socio-economic scenarios (also including GDP growth and land-use change) both derived from the SRES scenarios. The numbers presented in the table are based on the A1FI SRES scenario and the assumptions of a high climate sensitivity (4.5 °C) and globally uniform sea-level rise. Under this scenario, 97 cm of sea-level rise, compared to the level of 1990, is reached in 2100. Both assessments show that the expected number of people subject to annual flooding can be brought down significantly through adaptation.

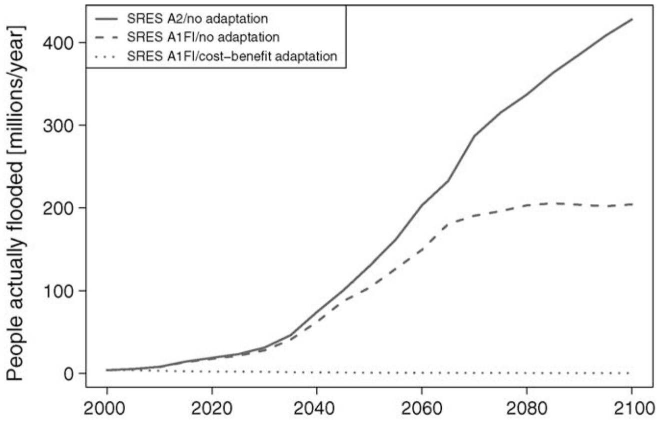


Fig. 4. Results form DIVA 2.0.3 on a global level: expected number of people subject to annual flooding (“people actually flooded”) between 2000 and 2100 for three different scenarios (SRES A2/no adaptation, SRES A1FI/no adaptation and SRES A1FI/cost–benefit adaptation).

A further improvement of DIVA compared to the previous global vulnerability assessments is the spatial and temporal resolution of the results. While Hoozemans et al. (1993) only considered two points in time and 22 world regions, DIVA produces results for every 5-year period with the smallest spatial resolution being more than 2000 subnational administrative units. As an illustration of these improvements Fig. 4 shows the evolution of the global expected number of people subject to annual flooding for three different combinations of SRES scenarios and adaptation strategies. How these numbers are then spatially distributed across countries and subnational-regions is shown in Figs. 5 and 6, respectively.

Both Hoozemans et al. (1993) and DIVA also assessed impacts on coastal wetlands. In addition to the different assumptions concerning scenarios discussed above, the wetland numbers are difficult to compare between the two assessments because different definitions of coastal wetlands were applied. Hoozemans et al. (1993) considered only RAMSAR sites, distinguishing three types of coastal wetlands: salt marshes, intertidal areas and mangroves. DIVA considered a wider range of coastal wetlands, also including non-RAMSAR sites and distinguishing six different types: coastal forest, high unvegetated wetland, low unvegetated wetland, freshwater marsh, saltmarsh and mangroves (see also McFadden et al., 2007b). The assessments also differed in terms of the adaptation measures considered. While DIVA explicitly took into account adaptation measures that directly act on the wetlands (i.e. wetland nourishment), Hoozemans et al. (1993) only considered the indirect and negative effects of building dikes. Results attained under the same sea-level rise and socio-economic scenarios as described above are shown in Table 4. The larger

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[1] We use the current DIVA version 2.0.3, which is not yet available for download.

Table 3
A comparison of global results between Hoozemans et al. (1993) and DIVA 2.0.3: coastal floodplain population and expected number of people subject to annual flooding.

	Hoozemans et al. (1993), (1 m), (2020), no adaptation	Hoozemans et al. (1993), (1 m), (2020), with adaptation	DIVA, A1FI, 2100, no adaptation	DIVA, A1FI, 2100, cost-benefit adaptation
Coastal floodplain population (millions)	396.8	396.8	257.1	257.1
Expected number of people subject to annual flooding (millions per year)	100.0	11.8	204.3	0.2

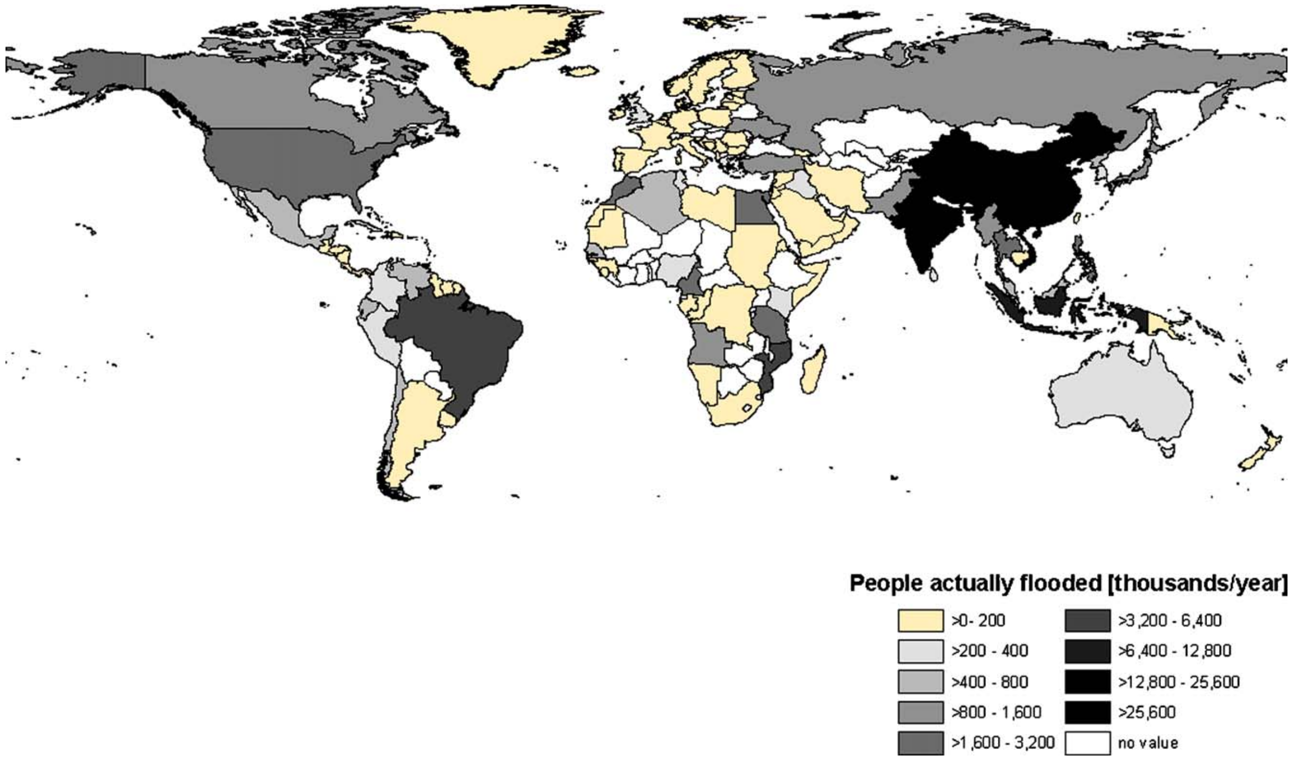

Fig. 5. Results from DIVA 2.0.3 on a country level: expected number of people subject to annual flooding (“people actually flooded”) in 2100 under the SRES A1FI scenario and no adaptation measures being taken.

Table 4
A comparison of global results between Hoozemans et al. (1993) and DIVA 2.0.3: loss of wetlands.

	Hoozemans et al. (1993) 1990, total area (km^2)	Hoozemans et al. (1993), (1 m), no adaptation, relative loss of area	DIVA, A1FI, 2000, total area (km^2)	DIVA, A1FI, 2100, no adaptation, relative loss of area	DIVA, A1FI, 2100, cost-benefit adaptation, relative loss of area
Wetlands (as defined in the respective studies)	302,000	59%	849,000	51%	39%
Mangroves (as defined in the respective studies)	134,000	56%	232,000	34%	29%

relative losses attained by Hoozemans et al. (1993) stem from the fact that a smaller and more fragile variety of wetland types was considered.

DIVA offers a great variety of additional impact indicators, such as land loss, people migrated, annual tourist arrivals. In addition, monetary values are placed on some of these impacts, as well as on the costs and benefits of measures to protect against these impacts (see Table 2).

7. Discussion

One of the major challenges addressed in the development of the DIVA tool was the integration of knowledge. The central concept here is modularity, that is, the idea of encapsulating expert knowledge in the form of self-contained modules and making them available to others via well-defined interfaces. Hence, modularity enables experts with different disciplinary backgrounds to integrate their knowledge without the need to understand the details of each other’s knowledge domains. Modularity also supports the analysis of model (or structural) uncertainty: the integrated model can be run with different modules that represent the same processes. An irresolvable drawback of the modular approach is that experts are not forced to study the other modules in detail; understanding the relevant modules’ interfaces is sufficient. As a consequence, modules might be based on conflicting assumptions or more efficient numerical algorithms cannot be found.

The second concept central to knowledge integration is iteration, a concept that is generally recognized as being important in transdisciplinary research (Klein, 1990). In the case of DINAS-COAST, it was crucial because the linkages between the coastal subsystems could not be specified at the beginning of the project.

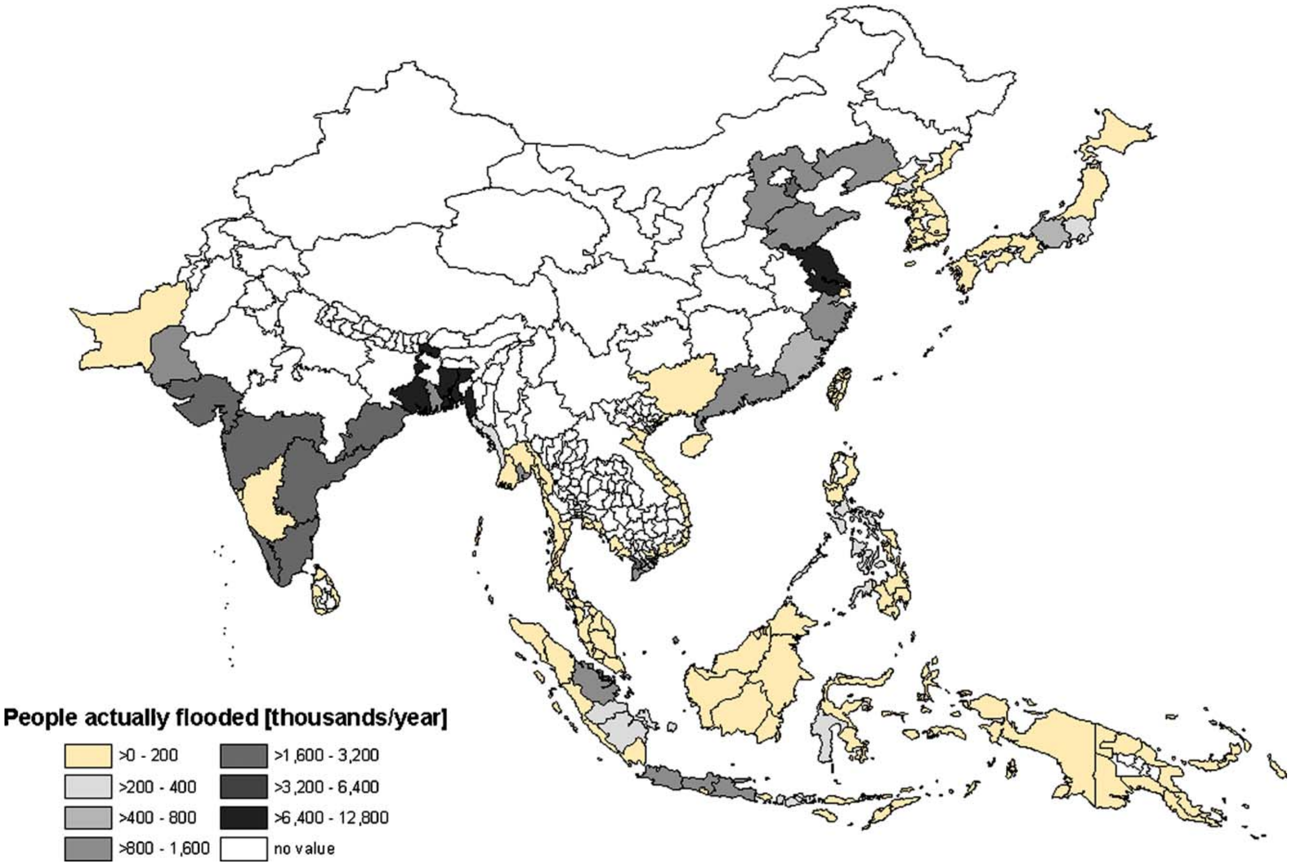

Fig. 6. Results from DIVA 2.0.3 on an administrative unit level for South-East Asia: expected number of people subject to annual flooding (“people actually flooded”) in 2100 under the SRES A1FI scenario and no adaptation measures being taken.

The iterative development thus allowed for taking advantage of the interdisciplinary learning that occurred amongst the participants during the course of the project. One caveat of the iterative approach is the danger of “iterating forever”. At some stage, the interfaces must be finalized in order to leave sufficient time for applying and validating the integrated model as a whole.

A crucial question about integrated models in general is validation. Integrated models are difficult to validate because of lack of data. Yet, there are three important arguments in favour of integrated modelling in the context of global vulnerability to sea-level rise. First, partial or component-wise validation is possible and has been done for the individual modules of the DIVA tool. Second, the integration of disciplinary subsystem knowledge is required in climate change research as decisions about the integrated coastal system are being made. Scientific integration is taking place anyway, in the sense that data produced by a study about one subsystem is fed into another one. DIVA improves the integration by also considering potential feedbacks and ensuring consistency of assumptions between the subsystem knowledge pieces. Third, DIVA is not meant to be a final product, but a living integrated hypothesis to be challenged by others. DIVA’s algorithms and data continue to be updated by the consortium whenever new knowledge becomes available. Furthermore, the free availability of the DIVA tool and method allows others to evaluate the work done so far and improve it by incorporating their own knowledge in form of data, scenarios or algorithms. In summary, DIVA is not meant to be a decision-support tool. A more appropriate term for DIVA would be a “discussion-support tool”.

The second major challenge was to make the integrated model directly available to a wide variety of end-users. A trade-off needed to be made between overall scientific complexity represented in the model and the communicability of results to users. A compromise was needed between the two aims of DINAS-COAST: to improve on previous global assessment efforts by including more realistic scenarios and by representing the dynamic interactions between natural and social coastal subsystems, and to make the model itself available to a broad audience. The more comprehensive and complex the model, the smaller would be the audience that can use the model and the more difficult it becomes to communicate model results. The GUI has been designed in such a way that a user, while confronted with much more information than in previous assessments, should be able to handle the information in ways that provide more insights than a published document can give. In hindsight, the development of the GUI might have benefited from greater interaction with potential users. However, given the limited time and financial resources a conscious decision was made to focus on the interdisciplinary knowledge integration described above.

The easy availability of the DIVA tool has already led to widespread application within various policy, academic and education contexts. DIVA contributed to a number of policy reports such as the one “The Future Oceans? Warming Up, Rising High, Turning Sour” by the German Advisory Council on Global Change (WBGU, 2006) and a report to the United Nations Framework Convention on Climate Change (UNFCCC) on adaptation options for coastal areas (Nicholls, 2007). It has been and is being used within several EU-funded projects such as PESETA, BRANCH, ADAM and CLIMATECOST, as well as in an integrated vulnerability assessment of coastal areas of South-East and East Asia funded by the Asian Pacific Network. Further scientific applications of DIVA include its use as a component in the Community Integrated Assessment System of the Tyndall Centre for Climate Change Research (Warren et al., 2008a,b) and the exploration of differential impacts due to different global patterns of sea-level rise at the UK Met Office Hadley Centre for Climate Change. DIVA has also been used in a series of regional workshops organized by the Secretariat of the UNFCCC, which aimed to familiarize national policy-makers with methods for assessing impacts, vulnerability and adaptation in preparation of their National Communications to the UNFCCC. At several universities, including those of Delft, Barcelona and Southampton, DIVA is used in the education of undergraduate and graduate students.

These applications of DIVA have made apparent a number of limitations. While DIVA was never meant as a decision-support tool for coastal planners and managers, there is a high demand for DIVA-like tools that operate at a resolution that is high enough for decision-making in the face of sea-level rise and associated hazards. Furthermore, the use of DIVA by people with detailed local knowledge of particular coastal areas has also revealed inconsistencies in the data (all data in DIVA has been derived from public global databases). Another limitation is that the DIVA GUI does not provide GIS functionality at the expert level. It is technically a minor operation to import and export to and from standard GIS tools, yet this functionality is not currently available via the GUI. Making such and other advanced functionality available via the GUI would, however, be a costly task, because GUI development does generally absorb significant amounts of resources.

Finally, there are a number of further drivers and processes that are assumed to have relevant contributions to coastal vulnerability, but could not be included into the current version of the DIVA tool, because of limitations in available data, models and resources. These include:

- Impacts of changing river sediment discharge on coastal erosion/ sedimentation;
- impacts of changing river sediment discharge, sea-surface temperature rise and acidification, as well as tourism on aquatic ecosystems (e.g., coral reefs);
- impacts of regional climate processes such as changing monsoon circulation, El Niño, La Niña and the Indian Ocean Dipole Mode;
- coastal development and urbanization;
- further adaptation options, such as, e.g., salinity intrusion barriers.

As a result of its modular structure and the flexible development process, the DIVA tool could easily be extended to address some of these limitations and to incorporate new knowledge and insights.

8. Conclusions and outlook

This paper presented the development of the DIVA tool, an integrated tool for assessing vulnerability to sea-level rise on national, regional and global scales. In this development, two major challenges needed to be tackled. First, knowledge from distributed partners about the various coastal subsystems needed to be combined into an integrated model in a way that allowed changing data, algorithms and subsystem interactions during the development process. Second, the integrated model needed to be made available in a suitable form to a broad community of end-users.

These challenges led to the development of the DIVA method, an iterative method for building integrated models by distributed partners. This method provides scientists from different backgrounds with a way to harmonize their conceptualizations of the system to be modelled and an intuitive interface to express their knowledge about it. Communication and collaboration is facilitated via automatically generated web-based documentation.

The DIVA method has been successfully applied to develop the DIVA tool, which is freely available for download from the DINAS-COAST website. The tool allows end-users to conduct their own assessments interactively—as opposed to model developers running their own model and publishing a selection of the results in a report. The free availability of DIVA has led to its broad application within the context of policy, research and education.

The DIVA tool is being further developed by members of the former DINAS-COAST consortium. The modular structure allows for easy updates of data and algorithms. Current work includes updating the data on elevation and areal extents using more detailed digital elevation models (Hinkel et al., under review). Further applications of the DIVA method are intended as well. It is conceivable to develop regional versions of the DIVA tool, such as a DIVA-Europe, a DIVA-South Asia and a DIVA-Caribbean. Increasing the spatial resolution of the analysis would increase the model's usefulness to coastal management.

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