

Environmental and ecological hydroinformatics to support the implementation of the European Water Framework Directive for river basin management

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ABSTRACT

Research and development in hydroinformatics can play an important role in environmental impact assessment by integrating physically-based models, data-driven models and other Information and Communication Tools (ICT). An illustration is given in this paper describing the developments around the Soil and Water Assessment Tool (SWAT) to support the implementation of the EU Water Framework Directive. SWAT operates on the river basin scale and includes processes for the assessment of complex diffuse pollution; it is open-source software, which allows for site-specific modifications to the source and easy linkage to other hydroinformatics tools. A crucial step in the world-wide applicability of SWAT was the integration of the model into a GIS environment, allowing for a quick model set-up using digital information on terrain elevation, land use and management, soil properties and weather conditions. Model analysis tools can be integrated with SWAT to assist in the tedious tasks of model calibration, parameter optimisation, sensitivity and uncertainty analysis and allows better understanding of the model before addressing scientific and societal questions. Finally, further linkage of SWAT to ecological assessment tools, Land Use prediction tools and tools for Optimal Experimental Design shows that SWAT can play an important role in multi-disciplinary eco-environmental impact assessment studies.

Key words | catchment modelling, eco-hydrology, environmental hydroinformatics, EU water framework directive, model integration, SWAT

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RIVER BASIN MODELLING FOR THE WATER FRAMEWORK DIRECTIVE

A worldwide increase in consumption of water has led to problems such as water scarcity and water pollution. A decrease in quantity and quality threatens human health and also impacts the environment and aquatic ecology. This awareness has induced more stringent legislation such as the European Water Framework Directive (WFD) (EU 2000). The WFD does not prescribe fixed measures or best practices, but promotes to elaborate a river basin specific planning where the different functions of water bodies, all sources of pollution and an active involvement of all stakeholders are integrated at the river basin scale with targets set for the desired ecological quality. The WFD imposes a planning process that consists of an identification of the system with an impact-effect analysis, the set-up of a programme of measures and the implementation and evaluation of the latter, supported by monitoring programmes for water physico-chemistry and ecology. This process requires the integration, synthesis, analysis and communication of large amounts of information and knowledge on the geophysical, biological, social and economical aspects in order to assist in the decision making process.

Although many environmental modelling methods exist, their practical application to support river management is rather limited (van Griensven & Vanrolleghem 2006). In particular for river restoration management, there is a need for tools to guide the investments needed to meet the ecological status targeted by the European Water Framework Directive.

In recent years, several practical concepts and software systems have been developed related to environmental decision support, e.g. Rizzoli & Young (1997); Paggio *et al.* (1999); Reed *et al.* (1999); Young *et al.* (2000); Booty *et al.* (2001); Lam & Swayne (2001); Argent (2004); Voinov *et al.* (2004). From a technical point of view, one can opt to build a new model for each application or to utilize existing models where possible. The first approach has the benefit of control in the models design and linkage, but requires a long model development period. The second approach saves on development time, but requires additional work to link existing models (Lam *et al.* 2004).

However, when suitable models are already available, it is probably the better option. The use of the linked models can also be a good start to learning what processes are of major

importance for the different simulations and which can be neglected. Since watersheds form the physical borders for river basin management, catchment modelling is the most appropriate reference frame for integrated modelling. Even though there exist several catchment tools and models in today's scientific community, their application has focused largely on scientific and not on societal questions. There is a need to simplify some of these tool sets, for example when developing decision support systems. In addition, it is of crucial importance to improve the dissemination of these tools to decision makers and stakeholders by education and training.

About 50 peer-reviewed papers already discussed the application of SWAT on pollution loss studies for a wide range of small to large river basins (Gassman *et al.* 2005). Several of these studies refer to the application of SWAT with regard to the US water quality legislation such as for Total Maximum Daily Load (TMDL) analysis or Best Management Practices (BMP). With the European Water Framework Directive in mind, SWAT was applied in the framework of several EU research projects on catchment modelling (Figure 1) such as in CHES (2001) to investigate the effect of climate change on water quality in European rivers, in TempQsim (2004) for the analysis of Mediterranean and semi-arid catchments with intermittent flow regimes, in EUROHARP (2004) for nutrient modelling studies and in BMW (2004) for the use in integrated modelling assessment. In the latter project, SWAT was successfully evaluated against the qualitative diffuse pollution benchmark criteria for the application of models for the Water Framework Directive, where it received a 'good' classification on 70% of the questions and at no point during the assessment a 'not recommended' for use (Dilks *et al.* 2003). SWAT has been applied in Europe for sediment, nitrogen and phosphorous predictions, among many others, in several watersheds in Finland (Grizzetti *et al.* 2003), several watersheds in Belgium (van Griensven & Bauwens 2005), in the UK (Dilks *et al.* 2003), for large scale applications in Europe (Bouraoui *et al.* 2005) and on low mountain range catchments in central Germany within the framework of the Joint Research Project SFB299 (Fohrer *et al.* 2002, 2005).

This paper describes initiatives with the Soil and Water Assessment Tool (SWAT) (Arnold *et al.* 1998) that were done

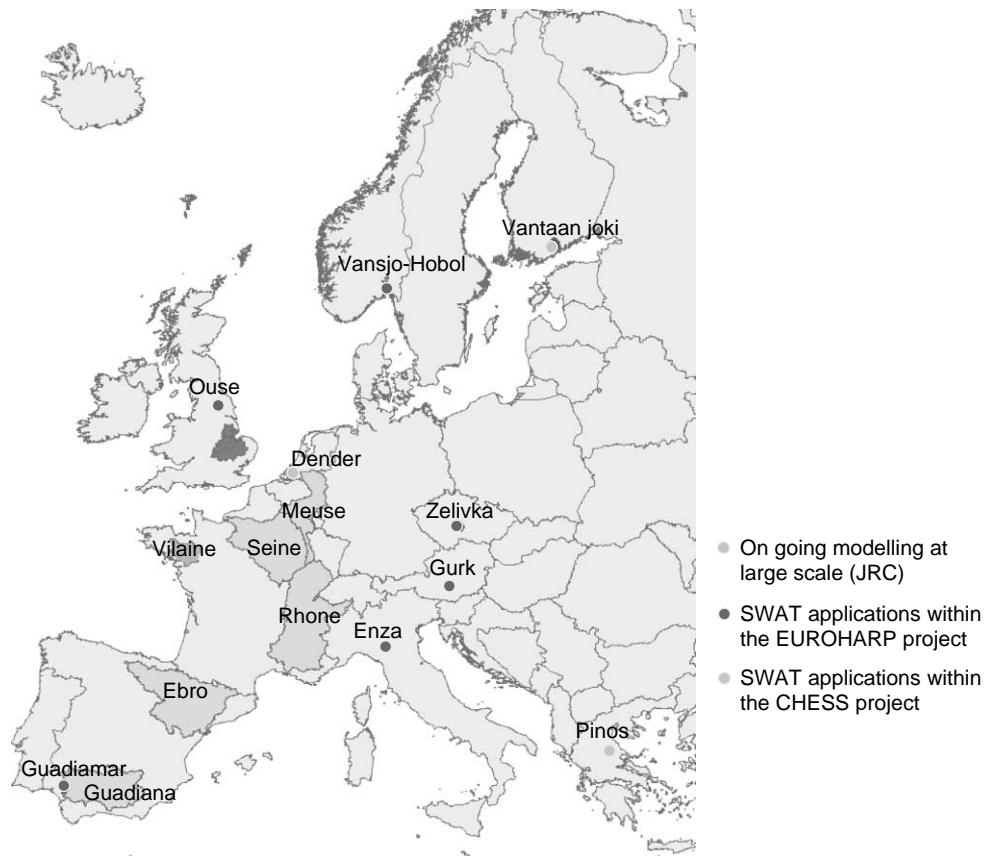


Figure 1 | Applications of SWAT model in EU funded projects.

over the last decade. SWAT appears to be a proper instrument for the assessment and prediction of point and diffuse pollution in river basins (Jayakrishnan *et al.* 2005). Since it has an open-source software policy, SWAT has a high level of flexibility for a wide range of applications by allowing the users to do case-specific adaptation to the source code and linking it to other models and modelling tools.

SWAT can be seen as a typical example of a hydroinformatics tool for ecological and environmental impact assessment and decision support (Mynett 2002; Mynett 2004)

SWAT

SWAT is a conceptual model that operates on a daily time step. The objectives in model development were to predict the impact of management on water, sediment and agricultural chemical yields in large basins. To satisfy these objectives, the model (a) uses readily available inputs for large areas; (b) is computationally efficient to operate on large basins in a

reasonable time, and (c) is capable of simulating long periods for computing the effects of management changes.

A command structure is used for routing runoff and chemicals through a watershed similar to the structure for routing flows through streams and reservoirs, adding flows, and inputting measured data on point sources (Figure 2). Using the routing command language, the model can simulate a basin sub-divided into grid cells or subwatersheds. Additional commands have been developed to allow measured and point source data to be input to the model and routed with simulated flows.

Model subbasin components can be divided as follows: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides and agricultural management. Hydrological processes simulated include surface runoff estimated using the SCS curve number or Green and Ampt infiltration equation; percolation modeled with a layered storage routing technique combined with a crack flow model; lateral subsurface flow; groundwater flow to streams

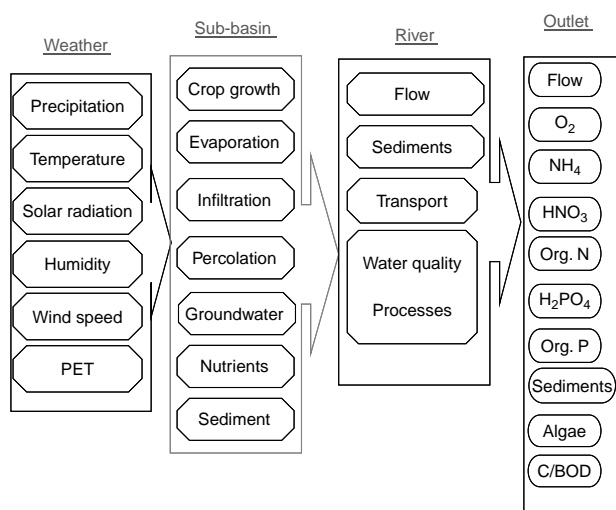


Figure 2 | Overview of the modules in SWAT.

from shallow aquifers; potential evapotranspiration by the Hargreaves, Priestley-Taylor or Penman-Monteith methods; snowmelt; transmission losses from streams; and water storage and losses from ponds (Arnold *et al.* 1998; Arnold & Fohrer 2005).

Channel routing is simulated using either the variable-storage method or the Muskingum method; both methods are variations of the kinematic wave model (Chow *et al.* 1988). The channel sediment routing equation uses a modification of Bagnold's sediment transport equation (Bagnold 1977) that estimates the transport concentration capacity as a function of velocity. The model either deposits excess sediment or re-entrains sediment through channel erosion depending on the sediment load entering the channel.

SWAT simulates the complete nutrient cycle for nitrogen and phosphorus. The nitrogen cycle is simulated using five different pools; two are inorganic forms (ammonium and nitrate) while the other three are organic forms: fresh, stable and active. Similarly, SWAT monitors six different pools of phosphorus in soil; three are inorganic forms and the rest are organic forms. Mineralization, decomposition, and immobilization are important parts in both cycles. These processes are allowed to occur only if the temperature of the soil layer is above 0°C. Nitrate export with runoff, lateral flow, and percolation are estimated as products of the volume of water and the average concentration of nitrate in the soil layer. Organic N and organic P transport with sediment is calculated with a loading function

developed by McElroy *et al.* (1976) and modified by Williams & Hann (1978) for application to individual runoff events. The loading function estimates daily organic N and P runoff loss based on the concentrations of constituents in the top soil layer, the sediment yield, and an enrichment ratio. The amount of soluble P removed in runoff is predicted using labile P concentration in the top 10 mm of the soil, the runoff volume and a phosphorus soil partitioning coefficient. In-stream nutrient dynamics are simulated in SWAT using the kinetic routines from the QUAL2E in-stream water quality model (Brown & Barnwell 1987).

AVSWAT: INTEGRATION OF SWAT IN GIS

An extension of ArcView[®] 3.x Geographical Information System (GIS) software was developed to support the SWAT model (Di Luzio *et al.* 2004a). This GIS software, named AVSWAT, provides a complete set of user-friendly and interactive input/output tools designed to help the user in performing numerous tasks, such as: delineating, segmenting and dimensioning the watershed from a digital description of the landscape (DEM, Digital Elevation Model); importing, formatting and processing the supporting data (i.e. land use and soil maps, weather station time series); formulating management scenarios and performing basic calibrations; analyzing and displaying output data from the SWAT model simulations (Figure 3).

AVSWAT was developed using AVENUE, the ArcView 3.x's object oriented programming language. ArcView Spatial Analyst extension was used to apply fundamental spatial analysis procedures for raster data, whereas ArcView alone provides spatial analysis capabilities using vector data. ArcView's Dialog Designer extension was used to embed plug-in controls, such as menus, buttons/tools, and ultimately build several dialog interfaces to help users accomplish a number of interactive tasks. Due to the implementation of standard format data sets, the applications of AVSWAT are not limited to a particular geographic location, thereby allowing applications around the world.

The current development of the GIS software, now named AVSWAT-X, provides users with an additional level of customized software tools (i.e. extension of an extension) that are designed to accomplish specific tasks. One such example (Di Luzio *et al.* 2004b) was developed to acquire,

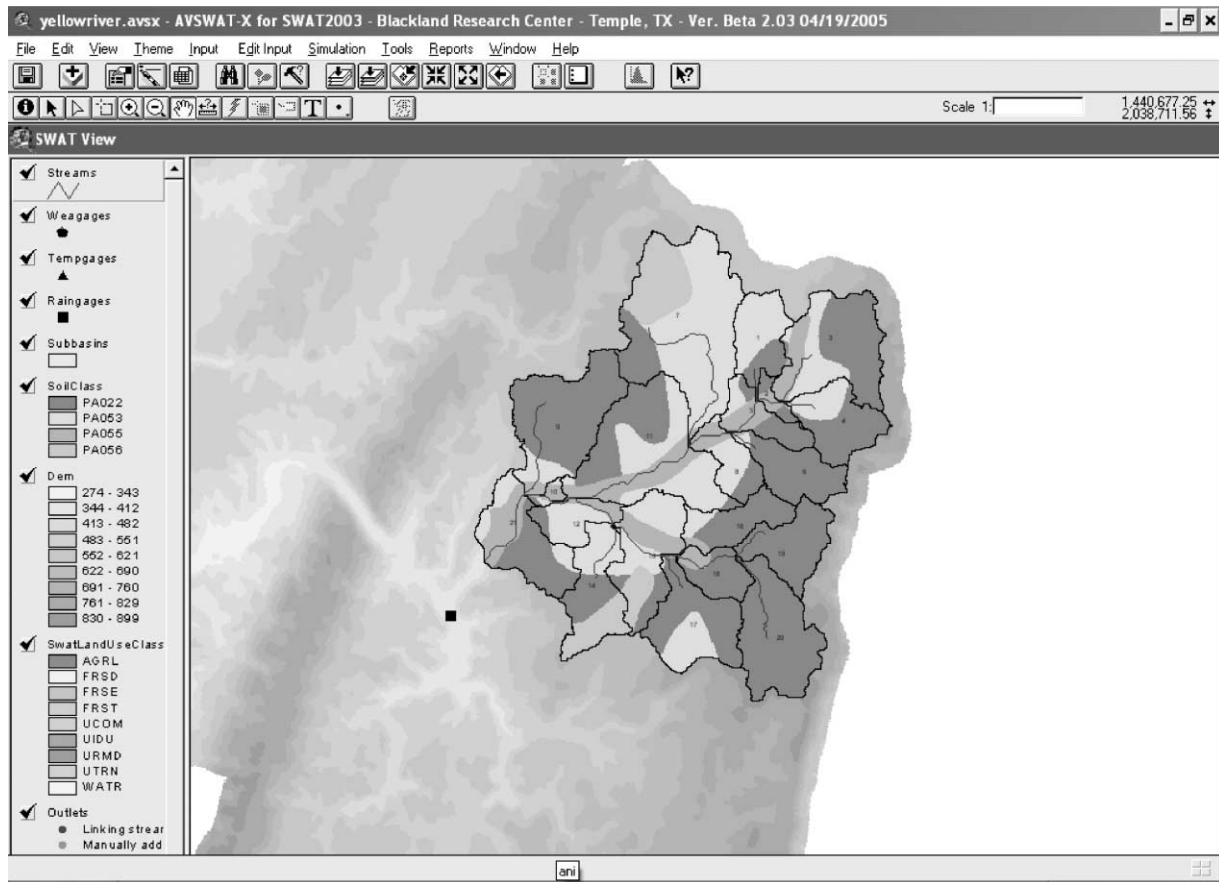


Figure 3 | SWAT view in the AVSWAT-X interface.

process and utilize Soil Survey Geographic (SSURGO) (USDA 1995) data sets, a more detailed alternative to State Soil Geographic (STATSGO) (USDA 1994) in the U.S. While a number of additional extensions are being developed, recent fundamental additions include: (a) a “splitting” tool that allows to disaggregate land use maps at the sub-pixel level to overcome the limitations of the readily available data sets, (b) a set of user friendly dialogs, which expedite the input-output management required by embedded procedures for the sensitivity analysis, automatic calibration and uncertainty analysis of the model, and which are described in the next section.

INTEGRATION WITH TOOLS FOR OPTIMISATION AND MODEL ANALYSIS

Due to their complexity, water quality models require specific methods for assessing their structure and predictive accuracy

and precision (Figure 4). Any quantitative assessment of water quality models must take into account three salient features of water quality models: (i) the immense number of parameters, (ii) the general lack of data available for model calibration and assessment and (iii) the fact that we know our models are far from perfect and have fundamental problems in simulating complex natural processes. All three of these problems intersect with the additional problem that water quality models are computationally intensive. For that reason, automated methods for model analysis and parameter calibration were designed for the SWAT model (e.g. van Griensven & Bauwens 2003; Eckhardt *et al.* 2003; Huisman *et al.* 2005). Recently, several other tools were developed directly within the SWAT model to enable execution of answers to the three features mentioned above.

First a simple yet robust sensitivity analysis tool “Latin Hypercube - One factor At a Time” (LH-OAT) (van Griensven *et al.* 2006) was developed for reducing the

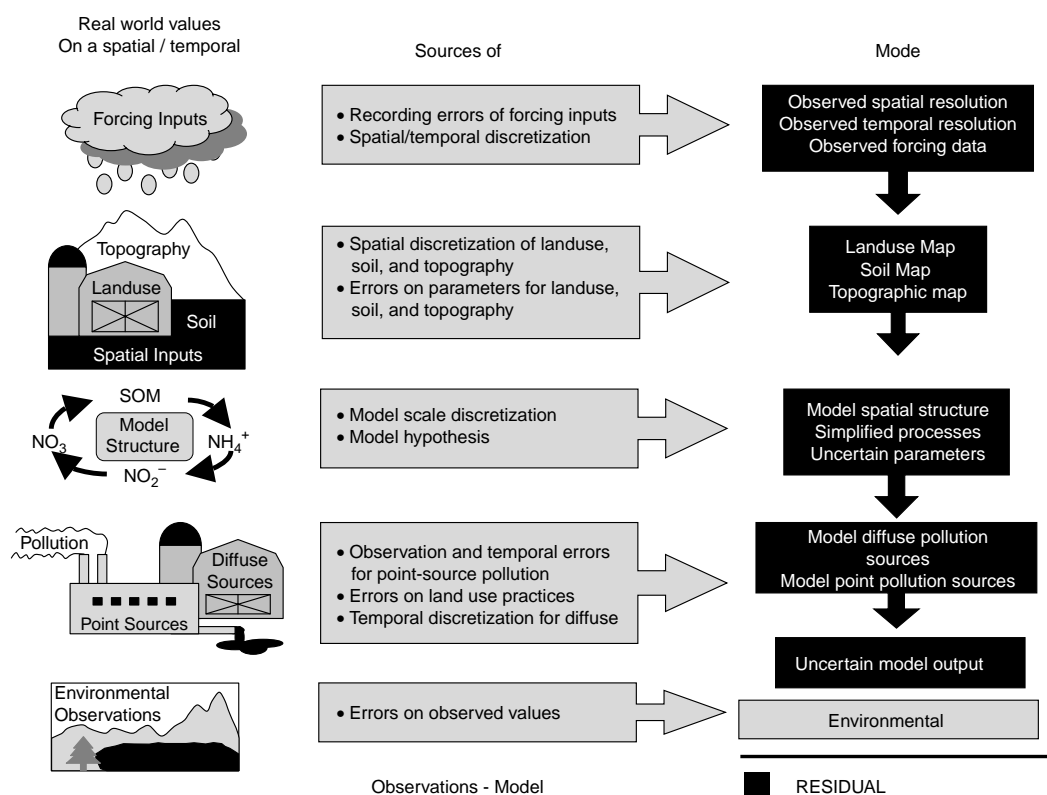


Figure 4 | Schematised sources of error in distributed water quality modeling.

high number of model parameters by defining the most sensitive ones. The method was designed to handle a large number of parameters and parameter non-linearities. LH-OAT combines the robustness of Latin Hypercube sampling that ensures that the full range of all parameters is being sampled in a computationally efficient manner. The One factor At a Time design assures that the changes in the model output can be unambiguously attributed to the parameter that was changed.

Second, a parameter calibration and parameter uncertainty assessment algorithm was developed based on special equations to deal with multi-objective problems in an efficient way. The algorithm "ParaSol" (Parameter Solutions) (van Griensven & Meixner 2006) was developed to perform optimization on model parameter for complex models with multiple output variables, such as SWAT. The ParaSol method calculates objective functions based on model outputs and observation time series. It aggregates these objective functions to a global optimization criterion. The objective function (OF) or the global optimisation criterion (GOC) are minimized

using the (SCE-UA) (Duan *et al.* 1992) algorithm. Finally, ParaSol performs a statistical analysis to calculate the parameter uncertainty and corresponding uncertainty on the model results. In addition, a tool was developed to carry out additional model verification using Split-Sample strategy in order to account for remaining uncertainties present in a water quality model, using the model bias as a simple assessment tool (SUNGLASSES).

MULTI-DISCIPLINARY INTEGRATION

Linkage to ecological modelling

Integration of ecological tools is facilitated by the fact that often simplified and inter-tuned models are used. So far, mainly data driven methods (e.g. artificial neural networks and classification trees) are preferred in this context, given their time efficient development (Goethals 2005). However knowledge based methods (e.g. fuzzy

logic, Bayesian belief networks) can be of considerable importance as well, in particular when enough data of good quality are lacking to develop data driven models (Adriaenssens *et al.* 2004).

A practical example of coupling SWAT results to ecological modelling is presented by Vandenberghe *et al.* (2005). This research was performed on the river Dender in Flanders. The river Dender is highly affected by nutrient inflow from agricultural and wastewater discharges from industries and households. Additionally, habitat modifications were established to ease flood control and guarantee boat traffic. These modifications have had a severe impact on the habitat characteristics and induced a completely different fish community compared to natural conditions. To gain a better understanding of these combined effects, water quality models of the Dender river were developed in ESWAT, a SWAT2000 version that was extended with hourly hydrological and water quality processes (van Griensven & Bauwens 2000). Pollution at the upstream boundary is estimated using daily water quality data for dissolved oxygen (DO), biologically oxygen demand (BOD), nitrate (NO_3^-), and ammonia (NH_4^+). Point pollution inputs comprise wastewater treatment plants outlets, industries and untreated household effluents. Land management and agricultural processes are taken into account to calculate diffuse pollution to the river.

The outputs of the model were used as inputs for ecological data driven models to predict presence or absence of fish species. These latter models allow predicting communities on the basis of the outcomes of the water quality model simulations and habitat data. For this purpose, classification trees were constructed on the basis of the Weka software (Witten & Frank 2000) using an algorithm to grow and prune so-called “C4.5” classification trees. A dataset was constructed on the basis of electrofishing data, collected in rivers of Flanders. In total, 168 measurements were used, of which in 50% of the cases pike was present. A training set of 112 instances was used for classification tree development, while 56 instances served for validation of the model. In both subsets, 50% of the instances were characterized by pike presence. In addition to the presence/absence of pike, seven variables (river characteristics) were available to induce the classification tree model: width, slope, depth, electrical conductivity, dissolved oxygen, pH, and water temperature. The most

optimal tree only used five variables to predict the presence/absence of pike (Figure 5).

The reliability of the model was proven by the prediction assessment in the validation dataset. About 71% of the instances was correctly predicted (CCI of 71 and Cohen’s Kappa of 0.43). The tree consisted of the following rule set as shown in Figure 5.

The results of the coupled models showed that long periods in low DO concentration led to below critical values for pike. Pike thus becomes endangered if the water quality (DO) decreases, which is mainly related to algae blooms as a result of nutrient inflow. On top of this the habitat quality is also seen to be very poor in the stem river, since the tributaries contain a very bad water quality. The remaining pike population is based on fish stockings, but when water quality is not improved, these activities seem to be useless. As such, the coupled models are very useful instruments to find the causes of ecosystem deterioration and also to test the potential effect of different restoration options. As an example, a scheme illustrating the comparison of the effects of different wastewater treatment options is provided in Figure 6. Based on the expected wastewater treatment efficiencies, the ESWAT water quality and quantity models allow to calculate the chemical changes in the river. Physical habitat measurements in combination with these water quality and quantity model outcomes, can serve as inputs for the ecological models. The overall predictions allow relating different measures with ecological effects. The latter can serve to calculate the ecological indicators as requested by the EU Water Framework Directive.

```

WIDTH <= 2.54
  SLOPE <= 0.8 : PIKE PRESENT
  SLOPE > 0.8 : PIKE ABSENT
WIDTH > 2.54
  SLOPE <= 0.3 : PIKE PRESENT
  SLOPE > 0.3
    EC <= 419 : PIKE PRESENT
    EC > 419
      EC <= 607 : PIKE ABSENT
      EC > 607
        DO <= 7.1 : PIKE ABSENT
        DO > 7.1
          DEPTH <= 0.5
            SLOPE <= 2.1: PIKE PRESENT
            SLOPE > 2.1: PIKE ABSENT
          DEPTH > 0.5 PIKE PRESENT
  
```

Figure 5 | Classification tree model for pike in the Dender river.

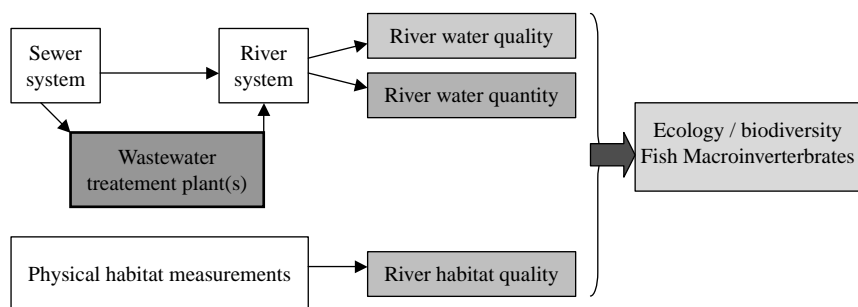


Figure 6 | Scheme illustrating the comparison of the effects of different wastewater treatment options by the coupling of SWAT model (representing river processes) and ecological models.

Integrated landscape modelling

Landscapes provide a wide range of service applications, comprising distributions of employment, economic income, habitats, water supply, or food production amongst many others (Costanza *et al.* 1997). Within the framework of the collaborative research centre SFB 299 (<http://www.sfb299.de>), the Integrated Tool for Ecological and Economical Modelling (ITE²M) has been developed to investigate landscape services for the peripheral Dill catchment (692 km²) in central Germany. ITE²M comprises of several

models addressing agro-economy (ProLand), agricultural policy (CHOICE) and environmental services with respect to the risk of heavy metals in soil (ATOMIS), water quantity and quality (SWAT), as well as faunal and floristic diversity (ANIMO, ProF) (Figure 7).

The agro-economic model ProLand

ProLand (Prognosis of Land use) assumes that land use patterns are a function of climate, soil type, biological,

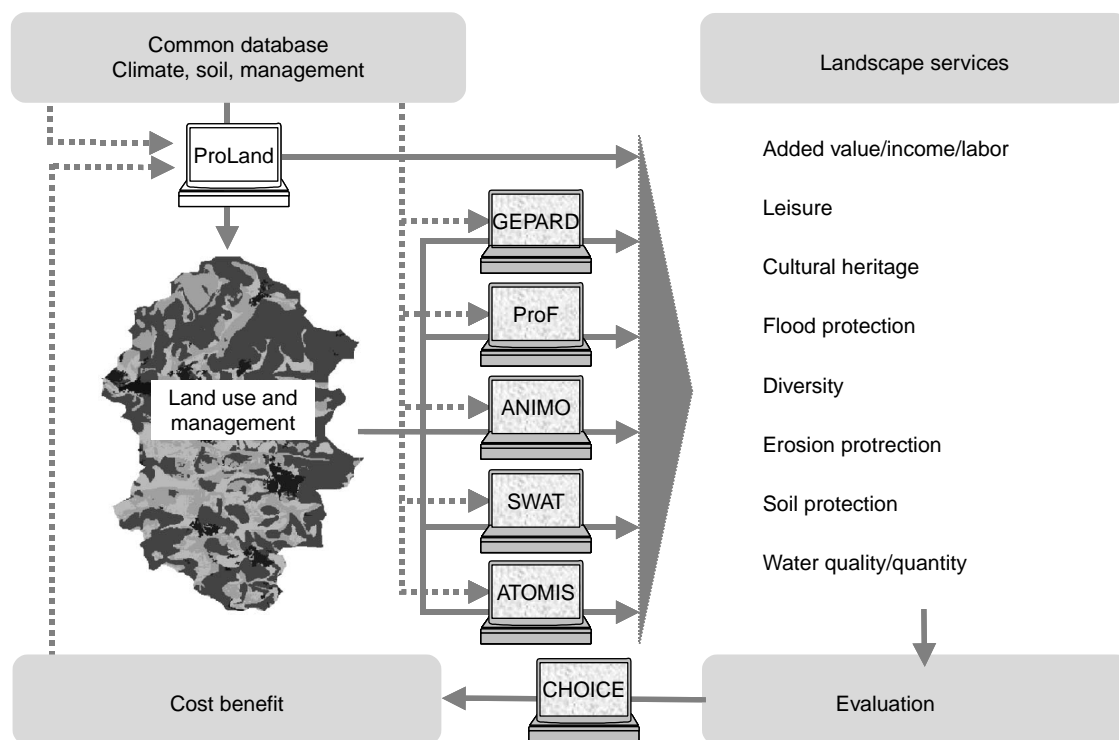


Figure 7 | Model and database structure of ITE²M.

economic and social conditions (Weinmann *et al.* 2005). The spatial distribution of these data form the basis for the allocation of land use systems, assuming land rent maximizing behaviour of the land user for any parcel of land. Land rent is defined as the sum of monetary yields including all subsidies minus input costs, depreciation, taxes and opportunity costs for employed capital and labour. As a result, two different types of model outputs are derived: (i) maps of the potential spatial land use distribution and (ii) sets of aggregated key indicators to characterise the economic performance of land use.

The eco-hydrologic model SWAT-N

A modified version of SWAT has been applied to predict hydrological and nitrogen fluxes on the landscape scale (SWAT-N, Pohlert *et al.* 2006). The hydrological components differ in the way of representing interflow by (i) simulating soil anisotropy and (ii) parameterizing the deepest soil horizon to account for the fissured rock aquifer characteristic in the Dill catchment. To improve the simulations of N turnover and export in the Dill catchment, SWAT was coupled to the mineralization and nitrification modules of the biogeochemistry model DNDC and to the denitrification module of CropSyst.

The biodiversity models ANIMO and ProF

The spatially explicit landscape model ANIMO (Steiner & Köhler 2003), a cellular automaton, quantifies the effect of land use change on regional diversity. The model assumes that each habitat (land use) has its own species inventory depending on environmental, regional and historical constraints. An intrinsic species pool is determined with its portions of habitat generalists and specialists. Single cells interact with neighbouring cells in the way that habitat generalists disperse into surrounding cells, whereas habitat specialists remain static. The number of species in a cell (α -diversity) is affected by the species inventory surrounding the cell (habitat dissimilarity, β -diversity). The overall γ -diversity of a landscape is the product of α - and β -diversity.

To assess floristic diversity the habitat model ProF (Prognosis of Floristic richness) is applied. ProF is a probabilistic GIS tool that is based on the mosaic concept. It assumes

that species richness is determined by habitat variability and heterogeneity and the proportion of natural, semi-natural and anthropogenic vegetation (Waldhardt *et al.* 2004).

The heavy metal accumulation soil model ATOMIS

The Assessment Tool for Metals in Soils (ATOMIS; Reiher *et al.* 2004) provides site-specific estimates of the fate of heavy metals such as Ni, Cu, Zn, Cd, and Pb in top soils. Metal input by land management is derived from ProLand data, whereas atmospheric input is taken from precipitation measurements. Metal concentrations in soil solution are calculated using general purpose Freundlich isotherms, considering soil sorption characteristics such as pH, SOC, clay and heavy metal content. ATOMIS identifies areas where geologic background in combination with site characteristics leads to potential enrichment of heavy metals due to agricultural land use and management. SWAT-N estimates on mean annual percolation rates from the top soil horizon and mean annual evapotranspiration rate are used as input for ATOMIS. Sustainability of land use and management options can be assessed by comparing the predicted future total metal concentrations to legally specified threshold values. ATOMIS outputs can finally be used by ProLand to calculate opportunity costs in terms of sustainable heavy metal criteria.

Trade-off and win-win situations

Integrating the results obtained by ITE²M can assist in the definition of sustainable land use concepts. Based on the same spatial land use and management information provided by ProLand the remaining members of ITE²M predict combinations of ecological landscape services such as faunal and floristic diversity, N export from rivers, groundwater recharge, or metal accumulation in soils. In combination with the economic services simulated by ProLand, trade-offs and win-win situation on land use and management can be predicted, as is shown in Figure 7 for the Aar catchment, a 60 km² subcatchment of the Dill catchment. The basis of this evaluation is an extensification of pasture management, the so called suckler cow land management scenario. In this scenario, cows and their offspring are kept on the meadows all year around to save infrastructural farmstead costs and labour. In the present

case study, the increase in economic value is accompanied by a slight increase in floristic diversity simulated by ANIMO and an almost constant groundwater recharge as predicted by SWAT (Figure 8). The relative optima of economic and ecological services can be depicted at an added value of about € 3 Million. This value is equivalent to a reduction in land cover of dairy pasture by -2.5% and cropland by -5.5% as well as an increase of 8% in extensive suckler cow management of the total land area as predicted by ProLand. In addition to this, ProLand not only calculates the overall changes in land management, but also provides spatially explicit information where these changes are best to be realized.

Further case studies of the overall model framework are presented in Fohrer *et al.* (2005) and Weber *et al.* (2001). ITE²M is a genuinely open concept that links models from several disciplines. Hence, the current estimates of landscape services are only limited by the selection of the number of ITE²M model members.

Optimal experimental design

Optimal sampling design techniques aim at the identification of sampling schemes to improve different aspects of the mathematical modelling process, according to explicitly stated objectives (Dochain & Vanrolleghem 2001; De Pauw & Vanrolleghem 2004).

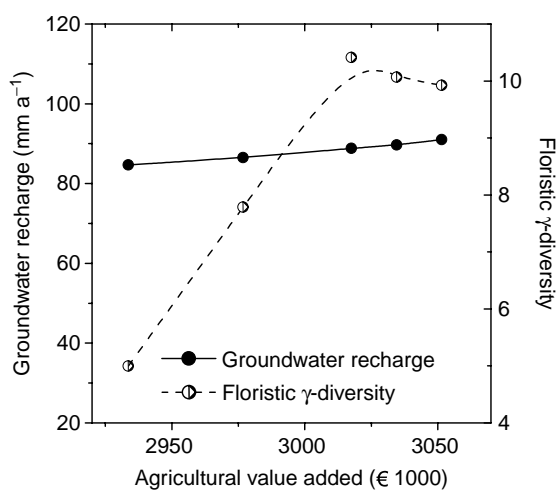


Figure 8 | Ecological-economic trade-offs for optimized suckler cow management as predicted by the integrated agro-economic model ProLand, biodiversity model ANIMO and SWAT (Breuer *et al.* 2004).

Vandenberghe *et al.* (2002) developed a methodology for an Optimal Experimental Design (OED) for water quality variables in a river with the purpose of increasing the precision of the parameters for the water quality module using SWAT. Different experiments (sampling schemes) will reveal more/less information and more/less parameter reliability (e.g. schemes that lack dynamics will provide less information than schemes with more). The method used is the D-optimal experimental design (Goodwin & Payne 1977; Walter & Pronzato 1999), which is the most general method for minimising the error on all estimated parameters.

In a D-optimal experimental design, the precision of the parameters is assessed by considering the determinant of the inverse of the covariance matrix of the parameter estimates (C) or Fisher Information Matrix (FIM) (Godfrey & Distefano 1985).

$$C(b) = \sigma^2(S^T Q S)^{-1} \quad FIM(b) = C^{-1}(b)$$

with b representing the model parameter vector, Q a diagonal matrix, the elements being the squares of the observation weights, and S the sensitivity matrix of the outputs to the parameters in comparison with the observations. Calculation of the covariance matrix based on the Jacobian matrix instead of the Hessian is acceptable when assuming linearity and having constant standard deviations on the observations (Bard 1974). The determinant of the FIM, $\text{Det}(FIM)$ is inversely proportional to the volume of the confidence region. Thus, by maximizing $\text{Det}(FIM)$, the volume of the confidence ellipsoids – and, correspondingly, the geometric average of

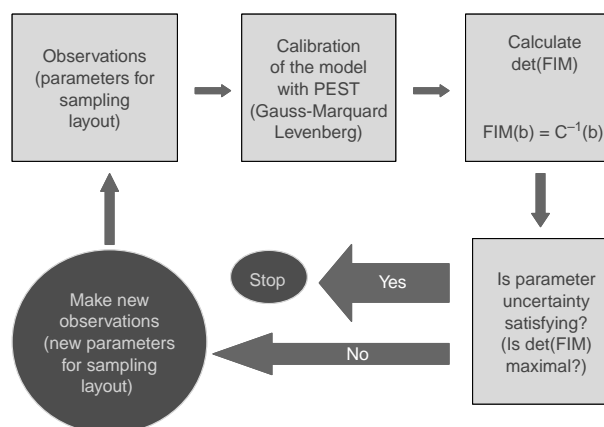


Figure 9 | Optimal experimental design for river water quality modelling (PEST = Parameter ESTimation model; Doherty 2000).

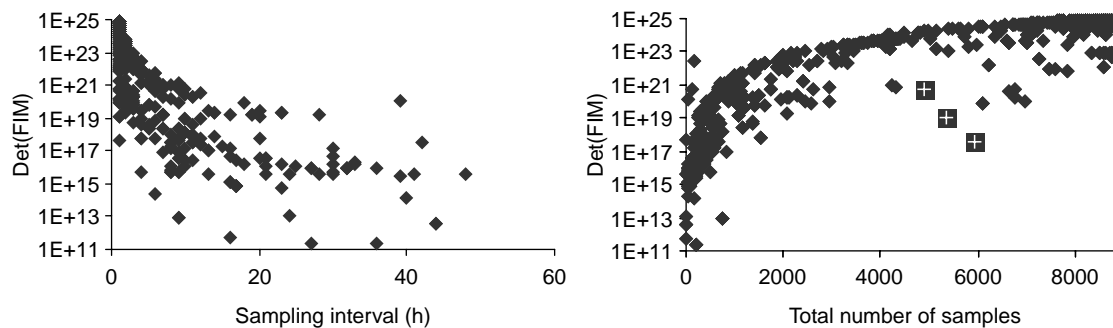


Figure 10 | The inverse of the Det(FIM) as a function of the sampling interval (left) and the total number of samples (right) (relatively bad strategies are marked with \boxplus).

the parameter errors - is minimized. D-optimal experiments also have the advantage of being invariant with respect to any scaling of the parameters (Petersen 2000). An extra aspect to be considered here is that for non-linear models the FIM is parameter dependent. The OED technique thus requires an initial data set to calibrate the model. Non-accurate parameter estimates may therefore lead to an inefficient experimental layout. This means that for the processes related to the non-accurate parameters better measurements could be identified. The design can only be approached by an iterative process of data collection and design refinement, known as a “sequential design” (Casman *et al.* 1988). Figure 9 shows the iterative scheme that is used to find the optimal measurements starting with a model that is calibrated with the currently available data. The different steps are explained in more detail hereafter.

The methodology has been applied for an OED at the Dender river whereby the frequency of the sampling and the period of sampling, the data type (only DO or combined DO-NO₃, DO-NO₃-BOD or DO-NO₃-BOD-NH₄) and sample locations (4 possible combinations of 3 possible locations: upstream, halfway, downstream) are considered as parameters for the sampling layout. The best way to take samples is (a) on an hourly time basis (Figure 10 left), (b) over nearly the whole year (8730 samples) (Figure 10 right), (c) in two locations (data not shown) and (d) of the four variables (data not shown). Whereas in general, low uncertainties are corresponding to a lot of samples (as expected), it can be depicted that other sampling schemes could be defined that provide a quasi similar accuracy, with fewer number of samples or at a lower frequency. The application of optimal experimental design for guiding

monitoring campaigns can thus point out better monitoring strategies and will eventually make the monitoring more effective with less cost.

CONCLUSIONS AND PERSPECTIVES

SWAT has been successfully applied world wide to address water quantity and quality issues. In general the model (along with useful GIS interfaces to process the readily available inputs) has yielded better watershed science and management. However the model and its input processing GIS interface tools were only the first step in providing hydroinformatics tools to decision makers within the context of the WFD. In this paper, SWAT and associated tools have demonstrated to be a useful tool to support the European Water Framework Directive and its explanatory guidance documents:

- **to do water management at the level of river basin;** SWAT operates on the river basin scale, includes processes for the assessment of the complex diffuse pollution sources and hence is a sound basis as a frame for integrated modelling.
- **to promote integrated management;** because SWAT is open-source software, it allows for site-specific modifications or easy linkage to other hydroinformatics tools.
- **to account for uncertainties;** SWAT incorporates algorithms for model analysis that enable the estimation of the model uncertainties and the evaluation of the fit-to-purpose of the model.
- **to support monitoring;** a joint use of monitoring and modelling is stimulated by linking of SWAT to an Optimal Experimental Design methodology

- **to set targets for ecological quality;** this is illustrated by the examples of linkage to ecological assessment tools as provided in this paper
- **to support public participation;** an important development around SWAT is the integration into the GIS post-processing tool AVSWAT that graphically displays the results.

However, applications in Europe can also be hampered by difficulties in data availability or the lack of regional databases. Only recently, the development of some European databases has been started (Breuer *et al.* 2003; Breuer & Frede 2006). Therefore, an integrated data and modelling tool such as the “BASINS” modelling environment for the US (Di Luzio *et al.* 2002), would be of great necessity. In such a modeling environment several homogenized data on land use, soil properties, climate conditions, river networks, discharges, point sources etc. can be provided and formatted for direct use. Within the European multi-national structure with its different data policies, as well as multi-faceted ways of soil and land use classification, one of the main difficulties lies in the data homogenization itself. Also, more developments would enhance external use of the SWAT model results. Important benefits could be obtained from a further integration into an internet interface to allow for web-based simulations or web-based post-processing of the model results. Finally, an open source policy for not only the SWAT model but also for the GIS interface would stimulate further integration with other tools or would offer more flexibilities for case-dependent developments in model codes. In general, it can be concluded that Environmental and Ecological Hydroinformatics tools prove to be quite valuable for implementing the European Water Framework Directive for River Basin Management.

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