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Distributed surface-groundwater coupled model applied to climate or long term water management impacts at basin scale

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Abstract: Sustainable management of water resources imposes long term prediction of decision consequences at basin scale. Surface – groundwater coupled models of watersheds need to be integrated with a wide variety of tools simulating the meteorological, soils and farming inputs, among others. Due to its progressive grid system, the MODCOU hydrological model is well suited to such schemes. Current results on the climatology of the Rhône river basin and the Seine river basin are presented. They are an initial step towards the ultimate integration with water economics models and watershed management decision tools.

Key words: sustainable management, water resources, groundwater model, surface water mode, climatology, finite differences, Seine river, Rhône river, diffuse pollution, nitrates

INTRODUCTION

The rationale for undertaking water resources studies on a basin scale instead of on a project by project basis is based on the recognition that the search for best possible sustainable development scenarios need to integrate all possible dimensions of a particular solution (e.g., economic, environmental, social, etc). Accountable effects on water and land resources need to be spatially studied over the whole basin as a unity if proper mitigation of future conflicts over water utilization is sought.

Since the early sixties, both surface water and groundwater computer modeling algorithms have been developed (Bruch et al., 1973) as well as economic tools aimed at optimizing water management (Frankel, 1965). And until recently such developments were pursued targeting the fulfillment of the single purpose planning demands of governments or local authorities. This sector by sector approach has very often separated issues regarding surface and groundwater and led to environmentally unfriendly consequences.

Today, the needs of integrated and comprehensive water resources management are clearly expressed in the paradigm of sustainable development. Sustainability leads to the integration of all criteria related to water management and the prediction of their evolution over long time series. The recent awakening of the global society to climate effects now dictates to perform risk assessment of soil, groundwater, and land-use interactions based on the full description of carbon, nitrogen and other constituents pathways. This new approach has lead to recent experiments in coupled atmosphere/hydrology modeling including the atmosphere-vegetation-soil transfer processes. This paper reviews such on-going efforts undertaken in France.

1. MODCOU, SPATIALLY-DISTRIBUTED SURFACE TO GROUNDWATER COUPLED MODEL

Numerical solutions of the flow and transport equations governing the behavior of underground aquifers are either based on finite differences or finite elements algorithms (De Marsily, 1986). For reasons of computation complexity and husbandry of physical measurements used for calibration, finite differences are most often used. Popular solvers such as the USGS-MODFLOW package are efficient for small or easy problems, but become inefficient, or fail altogether, for large, complex problems. This is most often due to the lack of flexibility of their “kilt” grid design which is ill suited to multi-scale embedding and may necessitate a large number of cells for areas of uniform properties, thus slowing down the computation process. Finite elements meshes are well known for being more suitable for the geometric representation of boundary conditions and use less elements in the solving system.

The Centre d’Informatique Géologique of Ecole Nationale Supérieure des Mines de Paris has designed a unique finite differences solvers based on a progressive multi-scale grid which enables parsimonious though realistic design of models while reducing significantly computing time. These savings are of particular interest for long time series simulations of climate changes or the impact on underground storage (Fig 1).

Following this principle, the hydrological model MODCOU (Ledoux, 1980; Ledoux et al., 1989) is a spatially-distributed surface – groundwater coupled model. For every surface cell, surface runoff and deep infiltration are calculated from precipitation and potential evapotranspiration (Seguin & al, 1982) using a conceptual reservoir based approach. Surface runoff is transferred through the drainage network with transfer times that depend on topography (length and slope of the downstream cells) and a basin-wide parameter, the concentration time. Infiltration, on the other hand, contributes to groundwater which can be structured as a multi-layered aquifer/aquitard at a coarser resolution. Transfer to groundwater can be delayed through the unsaturated zone using a cascade of equal linear reservoirs (Nash, 1970). This infiltration flow contributes to the dynamics of the groundwater represented in each aquifer by a finite difference solution of the two-dimensional diffusivity equation. The resulting component is dynamically coupled to the water level in surface “river” cells, and therefore contributes to river flow.

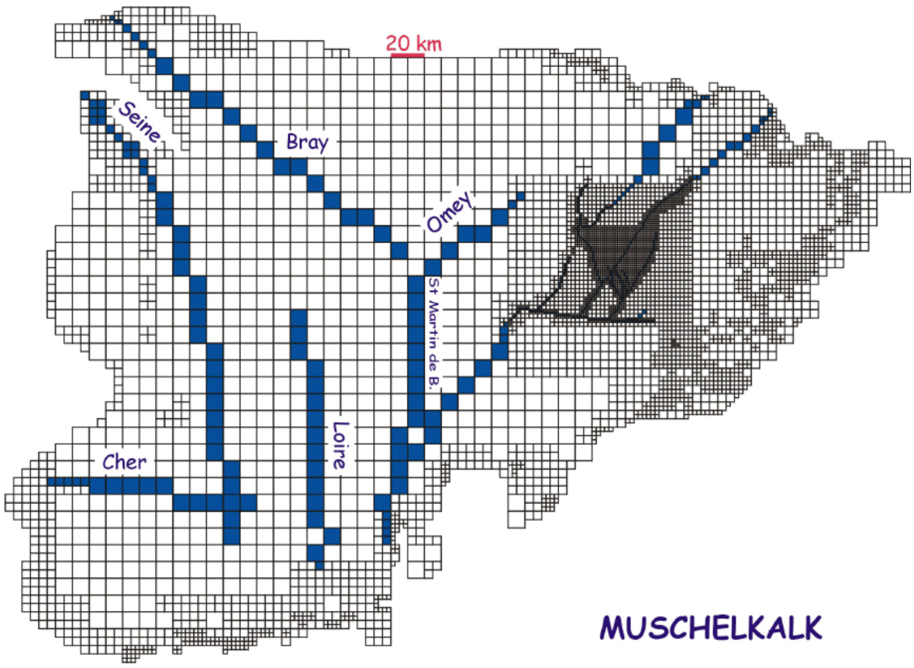

Figure 1. Multiscale MODCOU grid of the Trias – Muschelkak formation in the Paris basin. Model designed for simulation of the potential regional impacts of underground storage.

2. CLIMATOLOGY APPLICATIONS

The modular design of the MODCOU finite-difference model enables its efficient coupling with input producing or output consuming foreign simulation packages. For example, in the frame of the

GEWEX/Rhône project, a global system has been built to estimate the hydrological budget of the Rhône basin (Ottlé & al., 2001), one of the major European river (with a 86500 km2 watershed).

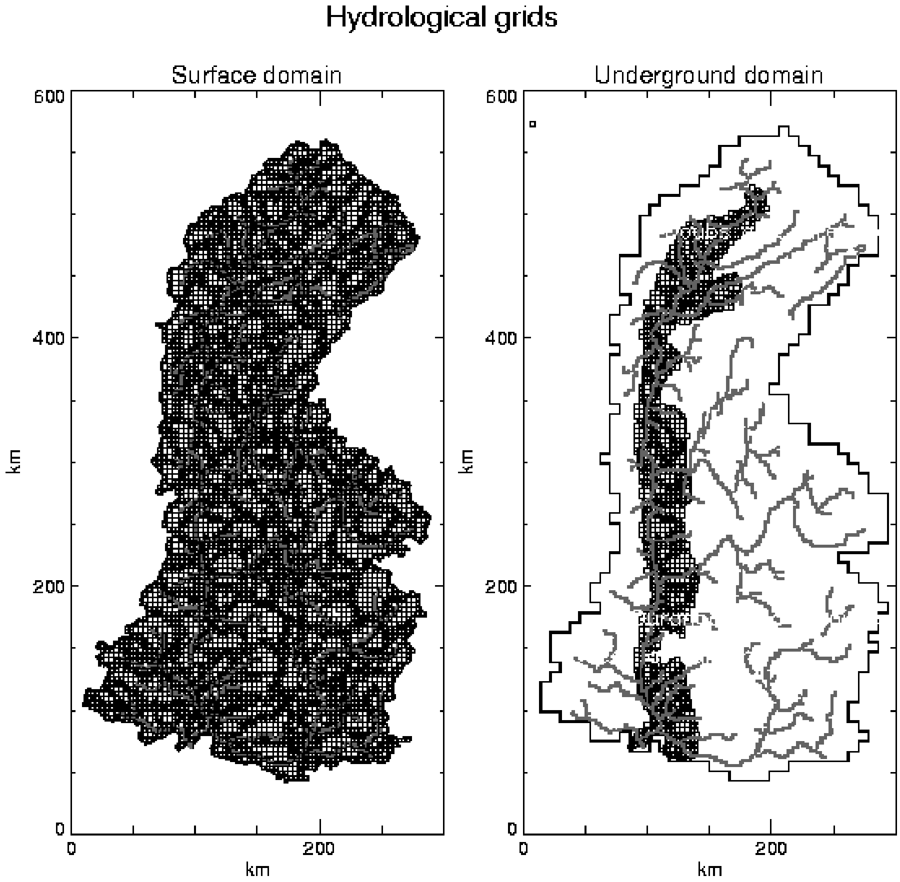

Figure 2. Surface and groundwater MODCOU grid models for the Rhône river simulation

The methodology is based on 4 models, one for each component of the hydro-meteorological system: SAFRAN for the atmospheric parameters analysis, CROCUS for the snow cover, ISBA for the surface water and energy budget and MODCOU for the underground transfers and the discharge estimation. The smallest element of the computing grid is 1 km^2.

This tool has been validated for 14 years (from 1981 to 1994) by comparing the daily flows simulated by the models with measurements of 145 gauge stations (Etchevers & al, 2001).

After calibration, the output of the GCM ARPEGE model has been used to estimate the hydro-climate of the Rhone watershed for the next 60 years. Strong contrasts in the hydrological response of the catchments have been identified depending upon the location of the sub-catchments and the evolution of the amount of precipitation.

In the Rhone basin, the simulation clearly shows the importance of topography and snow on the hydrological regime of the Rhone river and its tributaries. The simulated spatial variability of evaporation and total runoff are very large in the basin. Small annual evaporation and large runoff are found in the Alps because of the snow processes. On the other hand, the areas experiencing Mediterranean climate conditions (large annual global radiation, low precipitation) are characterized by negligible annual runoff. The simulation has been used as a reference to test aggregation methods accounting for the sub-grid variability of surface processes within a large area (128 km by 128 km). Habets et al. (1999) showed that the aggregated surface fluxes, drainage and runoff can be computed with an error lower than 5% provided that the sub-grid variability of precipitation, runoff and vegetation is taken into account. If these sub-grid processes are not aggregated, the errors in the simulation of the various terms of the water balance may exceed the annual reference by 20%

The MODCOU surface–groundwater coupled model has proven to be of a major contribution to the simulation of "what if" water management scenarios in France and abroad.

For example, in a country like Bulgaria were water resources are known to be limited, long term impacts of climate change need to be considered (O'Connor et al., 1999). The ISBA-MODCOU coupled model is being used operationally by the Bulgaria Meteorological Office on the Maritsa watershed (Artinian & Golaz, 1998) and is expected to contribute to a better long term conservation policy.

3. LONG TERM IMPACT OF FARMING PRACTICES IN THE SEINE RIVER BASIN

The latest ongoing application of MODCOU (Gomez et al., 1999) involves a systematic simulation of all compartments of the Seine river basin at a km scale including the stack of ten aquifers ranging from early Jurassic to Oligocene. This program is undertaken within the framework of the PIREN-Seine research program, devoted to the hydro-ecology of the Seine river basin (75000 km^2), with particular reference to the long term variations of nitrate concentration observed in some of the main aquifer formations.

The scheme involves a cascade of tools modeling the various components of the water cycle: MODCOU deals with surface and underground multilayered flows; the STICS, soil-agronomy model developed by INRA (Brisson & al., 1998), simulates the transfer of nitrates down to the root zone of crops and their water-nitrogen balance; NEWSAM models the dissolved matter fluxes in the groundwater and finally, SENEQUE (Billen, 1994) is used to for the simulation of nitrogen transport through the river network. The coupling between such a wide variety of modules is performed using a common GIS interface where problems of geometry registration and format conversion are solved.

The integrated model has been calibrated on the past 50 years history of point measurements in the aquifers and is presently used to simulate long term impacts of agriculture policies in the Seine area, in the sub-basins of Marne and Grand Morin. The parameterization of the agriculture practices in relation to nitrates output is performed over an 18 years period (e.g., 1970-1988) on the basis of observations performed by INRA (Mignolet, 2001). Farm statistics are regrouped by "Petites Régions Agricoles" (e.g., Small Farming Regions). These units have been defined since 1956 on the basis of homogeneity of soil, climate and farming practices. A total number of 550000 reference plots are regularly surveyed on a nation wide basis with a 10 years frequency in order to update the 159 regional farm statistics covering the Seine watershed. Each crop is characterized by a monthly growth and fertilizer calendar, as well as a typical STICS root model.

For the purpose of simulation scenarios of future evolutions of agriculture in the Paris basin, transition diagram matrices have been designed from observed past cropland evolutions on the period 1982-1988. These matrices are used to drive the time-wise modifications of the nitrogen fluxes entering the MODCOU/STICS model (Fig. 3).

4. PERSPECTIVES

The most recent challenging problem in computer-based watershed management is to perform a coupling of physical models with economic models (pricing, environmental valuation and investments) in order to address full conjunctive management issues for both surface and groundwater. Such coupling starts to be experimented with at local scale on well defined problems such as scarcity of water suitable for irrigation or human consumption due to saline intrusion in coastal water tables (Amigues & al. 1997; Caussade & al., 2000; Koundouri & Pashardes, 2001).

But the challenge of finding optimal strategies for planning and decision making in water management at basin scale is serious. The need for tight coupling between all model compartments as well the requirements of prediction over long time-series lead to a computational complexity which is well beyond currently available computing powers. Parallel algorithms and distributed computing are the most probable evolutions.

Furthermore, traditional conjugate gradient optimization algorithms do not fare very well with the control of parameters of complex hydrological models and are incapable of adequately dealing with the inherent non linearity of groundwater and surface water problems. Innovative optimization algorithms need to be experimented with such as fuzzy algorithms (Ganoulis et al., 1996) and artificial neural networks. The applicability of these new developments is also highly dependent upon the ability of the modeling tools to seamlessly interact with existing GIS and decision support systems.

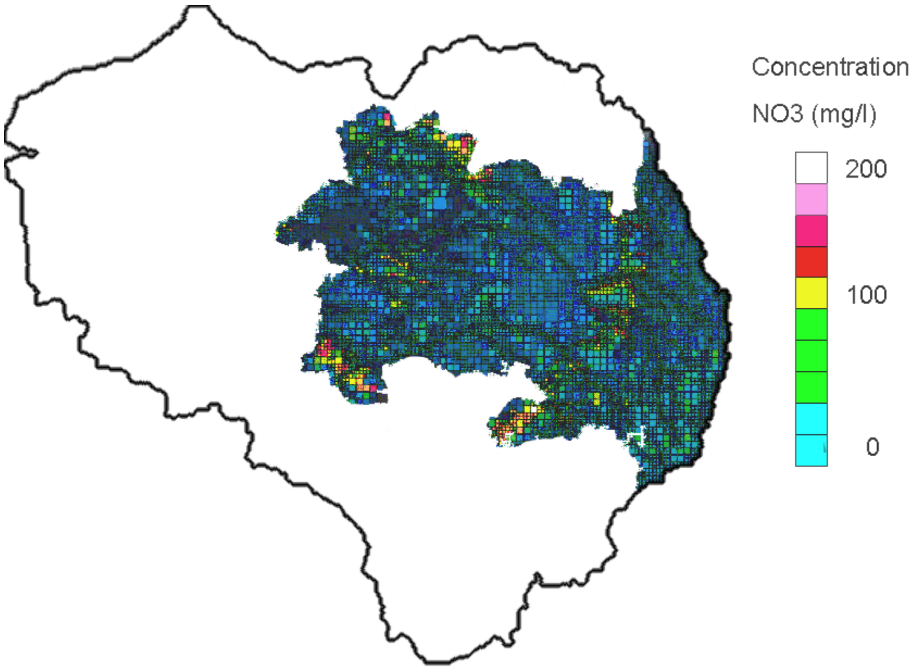

Figure 3. Simulated cumulated concentration map in NO3 (mg/l) within the Upper Jurassic aquifer of the Paris basin – Period May 1999. Results from MODCOU/STICS coupling (full extent of Seine river watershed is outlined)

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