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Modelling water scarcity across Europe in terms of water quantity and quality

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Abstract
The need for integrated and sustainable water resources management has become an important driver behind large-scale gridded modelling. Such modelling has traditionally focused on water quantity. However, reduced water quality can also limit water resources, particularly for drinking water. The water availability model GWAVA has been further developed to include a water quality module. This module will initially focus on biochemical oxygen demand (BOD). The module considers drivers of BOD loading from land, such as agriculture and urban runoff, and transport and loss of BOD through sewage treatment and river networks. In an exploratory assessment, GWAVA was used to produce maps of water scarcity across Europe. The new module enhanced those maps with effects of BOD on water resources. This enhancement increased the modelled proportion of Europe experiencing water scarcity, which indicates that it is important to include both water quantity and quality in model estimates of water scarcity.

Introduction

The requirement to manage water resources in an integrated and sustainable manner has become a driving force behind the use of large-scale gridded models (Xu and Singh, 2004). Such models have traditionally focused solely on water quantity. However, water quality is an important aspect, with cost implications for treatment if the water is not of sufficient quality for its intended purposes (Dearmont *et al*., 1998). Moreover, global drivers such as climate change are likely to have far-reaching continental and global impact on water quality. The Intergovernmental Panel on Climate Change has pointed out that many of the changes expected in water quality may be negative, including reduced dilution capacity of some rivers because of more frequent droughts, or increased pollutant loadings to other rivers due to changed rainfall patterns (Bates *et al*., 2008).

The large-scale gridded water resources model GWAVA (Global Water AVailability Assessment; Meigh *et al*., 1999) has been further developed to include a water quality module. This module will enable GWAVA to model nutrients, temperature and dissolved oxygen, although the initial focus is on five-day biochemical oxygen demand (BOD_5). BOD_5 is an indicator of the level of organic pollution which can limit municipal surface water use (Kowal and Swiderska-Broz, 1998). Further, it indicates the potential for oxygen depletion and eutrophication leading to reduced ecosystem health. The new water quality module produces monthly gridded maps of 5-arc-minute resolution of BOD_5 concentrations across Europe. Subsequently, it uses these maps to produce indices of the scarcity of water suitable for use.

This paper illustrates a preliminary approach used by the water quality module to model levels and pathways of BOD_5 across Europe from its sources (households, paved surfaces, industry, agriculture) to rivers, lakes, and wetlands. By combining this with modelled water quantities, an exploratory assessment is made of current water scarcity across Europe.

Methods

Water flows and BOD_5 fluxes were modelled with a monthly time step and on a 5-arc-minute grid resolution. Based on this, indices of water resources availability were mapped across Europe. This was done using the methods described hereafter.

Modelling water flows with GWAVA
GWAVA is a model for prediction of water resources scarcity at continental and global scales. It was developed by Meigh *et al*. (1999) with funding from the UK Department for International Development. Later, it was improved and extended in different regional and global research projects (e.g. Folwell and Farquharson, 2006; Fung *et al*., 2006). GWAVA estimates water scarcity on a cell-by-cell basis by comparing modelled river flows with modelled human demand for water (Figure 1). First, runoff is modelled considering vegetation, soil types and climate. Subsequently, this runoff is routed through the river network, lakes, reservoirs, wetlands, and artificial water transfers such as canals. Human water consumption is modelled considering population density, urbanisation, livestock, industry, irrigation, cropping, return flows, and groundwater to surface water use ratios.

During this study, GWAVA has been improved as follows: Certain crops typical for the European continent have been included in the calculation of irrigation water use. The simulation of crop growth has been extended with the possibility to vary growth season length with climate. Also, the spatial resolution of GWAVA has been improved to 5 arc minutes, in order to make use of the higher resolution datasets that are currently available for Europe.

GWAVA has not been calibrated in this initial assessment, although this will be undertaken in the future. Only basins where there was good agreement between GWAVA modelled and observed flows were chosen for the assessment of BOD_5 performance.

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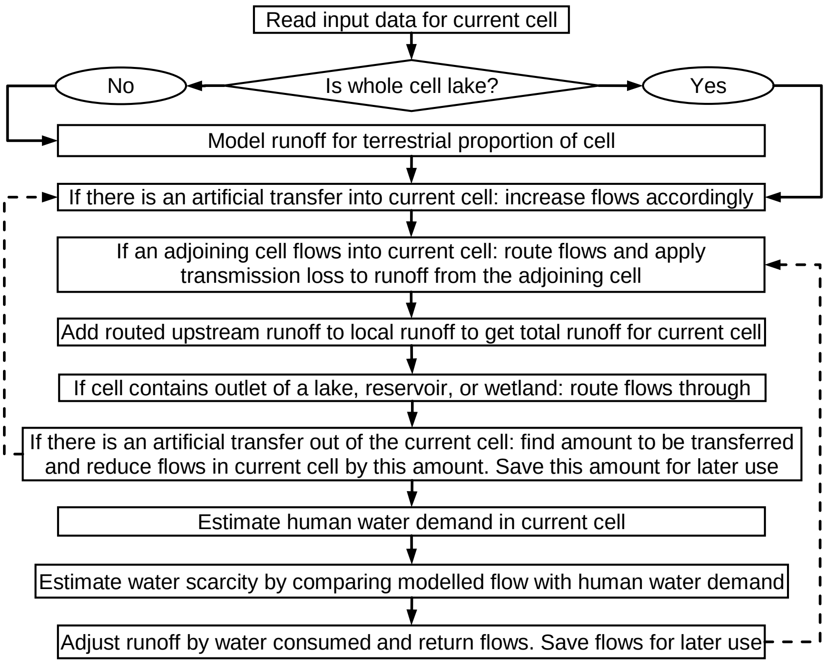

Figure 1 *Structure of GWAVA illustrated for a single grid cell (based on Meigh et al., 1999). Transfer of data to and from different cells is indicated with dashed arrows.*

Modelling BOD_5 emissions to water

Emissions of BOD_5 from land to rivers, lakes, reservoirs and wetlands are modelled as the sum of emissions from point and diffuse sources.

Point source loading of BOD_5 is modelled with a mass balance approach. This approach distinguishes point sources arising from households, industrial discharges and runoff from paved urban areas. BOD_5 from households is modelled using *per capita* BOD_5 emission, sewage treatment efficiencies, rural and urban population density and the fraction of the rural and urban population connected to sewage treatment works. BOD_5 from industrial discharges is modelled using the spatial distribution of six industrial sectors, their return flows and typical BOD_5 concentrations in these return flows. In addition, removal of BOD_5 in treatment of industrial sewage is considered. BOD_5 in runoff from paved urban areas is modelled using rainfall, urban area, population density, and reported BOD_5 concentrations in urban runoff.

Diffuse source loading of BOD_5 from scattered settlements is modelled identical to loading from households, except that sewage treatment levels are different. Agricultural diffuse loading of BOD_5 is modelled using a calibrated export coefficient method in which measured annual average load at catchment outlets was regressed against catchment characteristics. Catchment outlets used for the regression were located at water discharge monitoring stations with nearby stations monitoring BOD_5 (EEA, 2010). Considered explanatory variables were catchment area, cropland area, built-up area, livestock units, Köppen–Geiger climate, lake area, and variables used in modelling loading from point sources and scattered settlements. Regression using data from 1990, 1995 and 2000 invariably showed that the number of livestock units, point source loads and runoff are the only significant ($p<0.05$) explanatory variables. The equation thus obtained has an R^2 of 0.92 and has the following form:

$$\mathrm{BOD} = 3.79\,lsu + 0.167\,point + 1.57\,r \qquad (1)$$

Here, *BOD* is area-specific BOD_5 load (kg km^{-2} $year^{-1}$), *lsu* is number of livestock units per km^2, *point* is area-specific BOD_5 load from point sources and scattered settlements (kg km^{-2} $year^{-1}$), and *r* is runoff (mm $year^{-1}$). To prevent double counting of in-stream losses of BOD_5 from point sources and scattered settlements, the regression coefficient for *point* was set to 1 before applying Equation (1) to individual grid cells.

Modelling BOD_5 transport in water

The transport of BOD_5 after emission from point and diffuse sources is modelled by assuming that BOD_5 is transported downstream with discharge through river reaches, lakes, wetlands, reservoirs and artificial water transfers. While being transported downstream, BOD_5 is removed from the river network with gross water abstraction and by sedimentation and oxidation. The latter two removal processes are assumed to be proportional to BOD_5 concentration. Modelled values of water discharge and gross water abstraction are obtained from GWAVA.

Volumes of water in lakes, wetlands, reservoirs and river reaches are used to convert BOD_5 loads to concentrations and to estimate the loss and travel time of BOD_5 in the river network. Surface water volumes are estimated using data on land surface morphology.

We will now summarise the method used to calculate BOD_5 concentration (C) in kg m^{-3}. From conservation of mass and assuming complete mixing, the following differential equation was derived:

$$\frac{dC}{dt} = \frac{X^{in}}{V} - C\left(\frac{Q_r + Q_a + Q_{tr} - dV/dt}{V} + p\right) \qquad (2)$$

Here, X^{in} is the BOD_5 loading entering the cell (kg s^{-1}), V is the surface water volume of a cell (m^3), Q_r is the river discharge leaving the cell (m^3 s^{-1}), Q_a is the gross abstraction of water (m^3 s^{-1}), Q_{tr} is the water outflow through artificial transfers (m^3 s^{-1}), and p is a loss rate constant for BOD_5 (s^{-1}). The value used for p is 2.66×10^{-6} s^{-1}, which corresponds to 0.23 day^{-1} being a common value for large streams with average velocity (De Smedt, 1989). Equation (2) was solved resulting in an estimate of C for every grid cell in each month of the modelled time period.

The BOD_5 loading into the grid cell (X^{in}) is calculated as follows:

$$X^{in} = \sum_{i=1}^{n} Q^{in}_{r,i} C^{in}_{i} + \sum_{k} Q^{in}_{tr,k} C^{in}_{k} + X_t \qquad (3)$$

Here, n is the number of upstream neighbouring cells ($0 \leq n \leq 8$), $Q_{r,i}^n$ and C_i^n are outgoing discharge and BOD_5 concentration, respectively, in neighbouring upstream cell i, $Q_{tr,k}^n$ is the water flux from incoming artificial transfer k and C_k^n is the concentration in the grid cell where transfer k is coming from. Variable X_t is the BOD_5 loading from diffuse and point sources in the cell (kg s^{-1}).

The surface water volume of a cell, V, comprises both river reaches (V_r) and impoundments such as lakes, reservoirs and wetlands (V_l). Therefore, V is calculated as:

$$V = V_r + V_l \tag{4}$$

Values of V_l are modelled by GWAVA, and V_r is calculated in the new water quality module as:

$$V_r = d \cdot w \cdot l \cdot m \cdot f_{land} \tag{5}$$

Here d is river depth (m), w is river width (m), l is the river length without meandering (m), f_{land} is the fraction of land not covered by lakes, wetlands, or reservoirs, and m is a meandering factor defined as actual river length divided by l. River depth, d, is calculated largely according to Pistocchi and Pennington (2006) using river bed slope estimated from sub-grid elevations, and grid-cell discharge. River width, w, is estimated using grid-cell discharge according to Allen *et al*. (1994). Meandering factor, m, is calculated as a function of grid cell size according to Fekete *et al*. (2001).

The model of BOD_5 transport in water has not been calibrated in this initial assessment, although this will be undertaken in the future.

Indices of water resources availability

GWAVA produces a number of indices of water scarcity. In this study, GWAVA's Water Availability Index 4 (WAI4) was used. WAI4 characterizes the frequency of water scarcity conditions as:

$$WAI4 = min\left[\frac{avail10_i - dem_i}{avail10_i + dem_i}; i = 1,2,\ldots,12\right] \tag{6}$$

Here, $avail10_i$ is the multi-annual 10th percentile water availability ($m^3 s^{-1}$) for month i, and dem_i is the multi-annual average water demand ($m^3 s^{-1}$) for month i. The term 'multi-annual' indicates that the calculation involves one value for month i in each year of the modelled time period, as opposed to multiple values within the duration of one month. WAI4 is between 0 and 1 in cells with sufficient water resources and between 0 and –1 in cells with regular occurrence of water scarcity.

In addition to WAI4, we made a new index for the scarcity of surface water usable for municipal water abstraction. This new index, Usable Surface Water Availability 1 (USWA1), indicates the availability of surface water for one specific type of use: municipal surface water abstraction. USWA1 assumes that a location is not suitable for municipal surface water abstraction if there is any month in which the multi-annual 90th percentile BOD_5 level ($BOD90_i$) exceeds 4 g m^{-3}. The latter value is the highest BOD_5 concentration allowing municipal water abstraction according to Kowal and Swiderska-Broz (1998).

$$USWA1 = min\left[\frac{4 - BOD90_i}{4 + BOD90_i}; i = 1,2,\ldots,12\right] \tag{7}$$

Thus USWA1 is between 0 and 1 in cells with sufficiently low BOD_5 levels for municipal water abstraction and between 0 and –1 in cells unsuitable for municipal surface water abstraction.

In this paper, we indicate the scarcity of usable surface water with the distance to the nearest location with positive WAI4 and positive USWA1. Greater values of this distance indicate larger scarcity in terms of both water quantity and quality. Distances larger than the grid-cell width (between 3 and 9.2 km, depending on latitude and direction) are indicated.

Modelled time scales

All input data used in the modelling, except climatic input, represent the year 2000. Climatic input was monthly from 1960 to 2000, of which the first 30 years were used for model warm-up. Indexes WAI4 and USWA1 are simulated using the month-to-month variability in water availability and BOD_5 concentration resulting from variability in climate input from 1990 to 2000.

Results and discussion

Modelled BOD_5 concentrations were compared to measured concentrations at 89 monitoring stations (EEA, 2010) throughout Europe, covering the most common climate types and land surface morphologies. Measurement stations were selected based on the amount and continuity of their BOD_5 measurements. Further, we discarded stations at which measured discharge deviated more than a factor of 2 from the modelled discharge because this would indicate that the station is located in a different grid cell than where GWAVA assumes the associated river is. Figure 2 shows that the model reproduces the general pattern of high and low measured concentrations, although it under-predicts concentrations below 4 g O_2 m^{-3} with about a factor two. This is reflected by the coefficient of determination of 0.37. A reason for the under-prediction is that both GWAVA and the water quality module are not yet calibrated. In particular, we used a literature value for BOD degradation in rivers (p in Equation (2)) which might be too high in this application. Another reason could be that lower values of treatment efficiency of manufacturing influent are more appropriate. We are currently investigating this within the project SCENES from the European Commission.

GWAVA predicts that for the period 1990–2000 water scarcity in terms of quantity is concentrated in Mediterranean, arid and densely populated parts of Europe. This is indicated by larger distances to locations with a

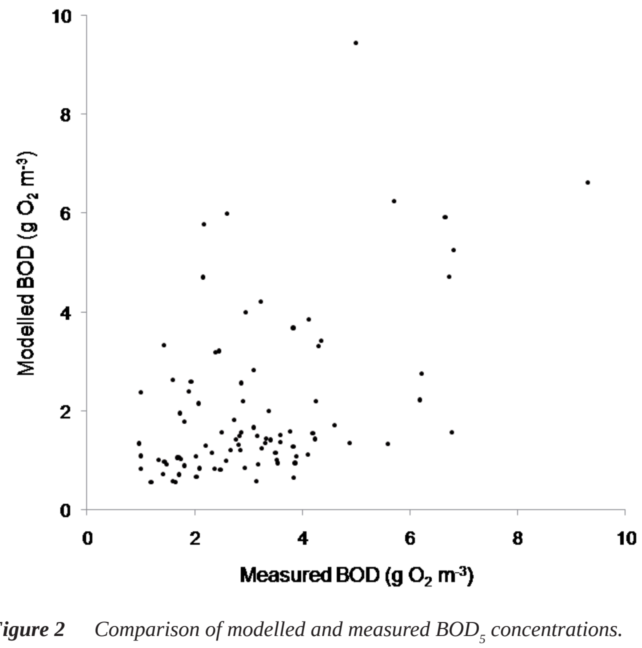

Figure 2 *Comparison of modelled and measured BOD_5 concentrations. Each dot represents the BOD_5 concentration at a monitoring station averaged over the year 2000.*

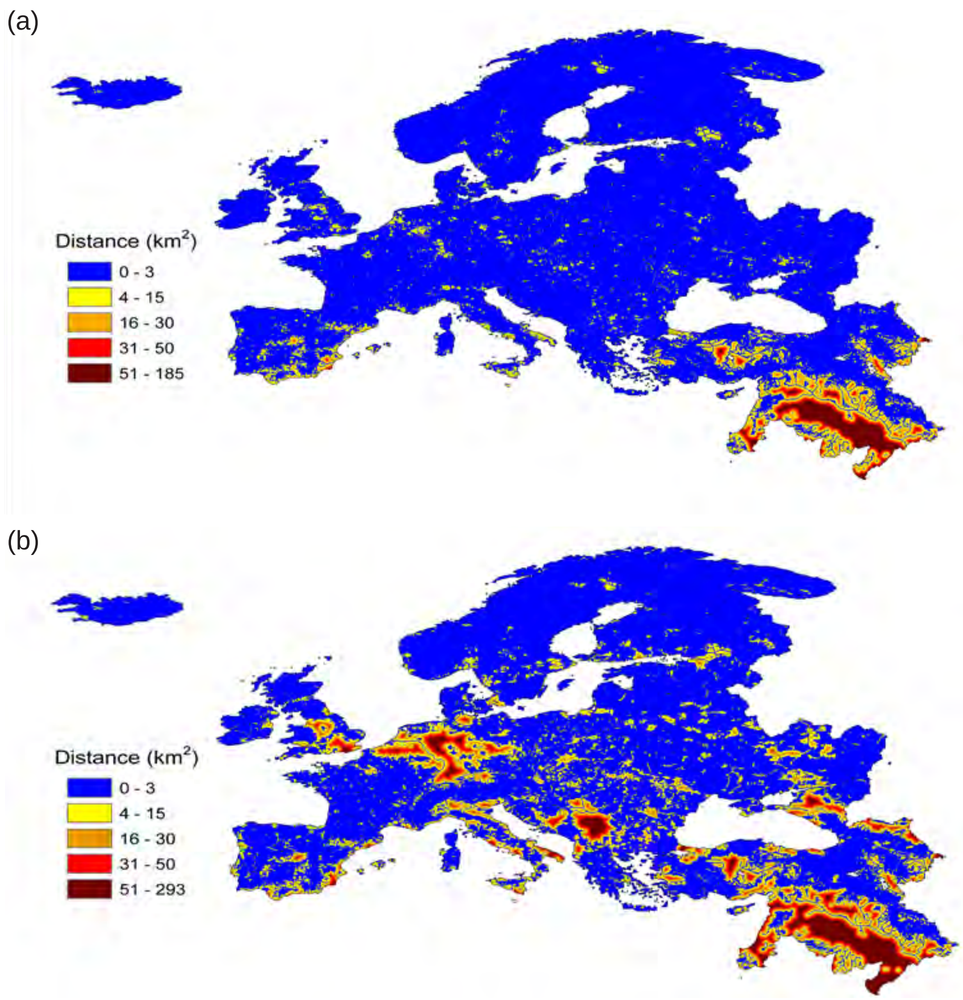

Figure 3 *Modelled water scarcity from 1990 to 2000 across Europe in terms of water quantity and quality: (a) distance to the nearest location where the available surface water quantity is sufficient to fulfil the human demand for water (WAI4>0), and (b) distance to the nearest location where WAI4>0 and where the BOD levels in the surface water are suitable for municipal water abstraction (USWA1>0)*

positive WAI4 in Figure 3a. Further, GWAVA indicates that some water scarcity in terms of quantity occurs in wetland-dominated parts of Scandinavia due to GWAVA's assumption that swamps cannot be used for water abstraction.

The under-prediction of BOD_5 concentrations (Figure 2), probably leads to underestimation of the spatial extent of scarcity of surface water suitable for municipal abstraction (USWA1<0). Another effect of the under-prediction is that the areas with a negative USWA1 are probably those with relatively large scarcity of suitable water.

Comparison of Figure 3b with Figure 3a indicates that a large proportion of areas with scarcity of surface water suitable for municipal abstraction is located close to areas where water quantity is scarce. In fact, between 35 and 60° N, about half of the cells with a negative WAI4 also have a negative USWA1. The reason is that areas with less water available per water consumer are often also the areas where less dilution capacity is available per polluter.

However, some areas with sufficient surface water nearby (Figure 3a) are located far from surface water of sufficient quality (Figure 3b). The reason for this can be that the *per capita* contribution to BOD_5 loading to water is particularly high. This is, for example, the case in much of Serbia and Montenegro where only about 10% of sewage is treated and where the manufacturing sector produces relatively much BOD_5 containing effluent. In some other areas, the combination of insufficient surface water quality with sufficient surface water quantity is mainly caused by high *per capita* loading further upstream. This is for example the case in the western German part of the Rhine catchment where scarcity of usable surface water is often caused by intensive livestock breeding and dense urban areas that are much further upstream.

Across Europe, the average distance to usable surface water when taking BOD_5 into consideration is almost two times larger than without (5.43 versus 2.72 km, respectively). This indicates that usable water scarcity is substantially underestimated when solely focussing on water quantity.

Conclusions

The exploratory assessment described in this paper indicates that it is important to include both water quantity and quality in model estimates of water scarcity even when we expect that we are underestimating BOD_5 concentrations. We combined the effect of available water quantity on water scarcity with the effect of BOD_5 level on water scarcity. The addition of the effect of BOD_5 level substantially increased the modelled proportion of Europe experiencing water scarcity.

More research is needed to improve the modelling of BOD_5. Further, it needs to include more water quality parameters in GWAVA's water quality module in order to better indicate scarcity of usable water. We argue that the resulting method will help integrated water resources managers by providing data that they require for the many reaches of rivers in Europe without water quality measurements. Further, it will provide them with an improved tool for generating future scenarios of water scarcity under managers by providing data that they require for the many reaches of rivers in Europe without water quality measurements. Further, it will provide them with an improved tool for generating future scenarios of water scarcity under different sets of assumptions about changes in driving forces such as population change, economic growth, climate change, or future commitments to wastewater treatment.

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