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Modelling the impact of water reuse strategies on hydrologic flows in the Blackwater & Chelmer catchments, UK.

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Abstract: Wastewater reclamation and reuse at various scales is an important resource management tool in many regions of Europe and is coming under increasing scrutiny in the UK. However, the impact of reuse strategies on hydrologic flows, particularly during dry periods, is poorly understood and yet crucial to the development of sustainable resource management policies. In this paper we summarise the integrated models used for the simulation of such strategies (river flows, soil hydrology, aquifer dynamics and water distribution) and describe how water demand 'profiles' can be incorporated into a distribution matrix to simulate recycling scenarios and demographic changes, and how both inter-catchment transfers and water importation schemes are implemented within the model. We highlight the strengths and limitations of both the modelling methodology and its application in this context, noting in particular how the approach supports consideration of new infrastructure configurations, and the simulation of spatially variable consumer behaviour and other regional development and land-use plans. Simulation outputs show that low to medium uptake rates of in-house water recycling devices (<30%) are unlikely to have significant impacts on catchment water balances. Conclusions suggest that the connectivity of the hydrological system in the Chelmer & Blackwater appears to provide robustness in the face of water recycling schemes, but regional schemes, which do not transfer water across catchment boundaries have the potential to adversely influence both hydrological flows and river water quality.

Keywords: Water reuse; modelling; catchment; water policy.

1. INTRODUCTION

Tensions inevitably occur between science, policy and the world as it is interpreted and negotiated by different actors-including scientists and policy makers. Knowledge generated by scientific research can be difficult to assimilate and exploit. It also tends to be determined by the agenda and interests of the scientist and the body funding the work. By focusing upon the range of responses and interpretations at the local level, policy relevant research moves from the disaggregate to the aggregate. By contrast, policy and policy research, in common with much science, invariably adopts a top-down approach that is grounded in the aggregate and applied to the disaggregate.

Simulation models of hydrologic processes are widely used to support exploration of policy options as part of broader water resource management planning. In such contexts, modelling teams often struggle to maintain a balance between scientific rigour, and usability (from a lay stakeholder perspective). Furthermore, the investigation of 'new' phenomena (in this case water recycling) can be restricted by application of models which have limited scope (i.e. represent a limited range of phenomena).

The activity described below addresses the issues of science – user interfaces and integrated modelling in a praxis oriented study of water recycling options within a catchment located in Southern England. This is achieved through use of an Integrative Modelling Framework which seeks to couple related hydrologic processes to provide a strategic view of system modification.

2. THE INTEGRATED MODELS

The models constituting the Integrative Modelling Framework were developed from the integration of existing models of hydrological flows across catchments [Billen et al 1990; Allen et al 1996], and of aquifer flows, slope hydrology and irrigation [Oxley et al. 2002].

The Integrative Modelling Framework we describe retains most of the characteristics of each individual model, and, by using a common central database and a high level driver - which co-ordinates the disparate temporal and spatial scales - is able to present these characteristics within a more holistic framework whereby the interactions between the sub-models highlight many of the critical dynamics of change which previously could only be dealt with through user definition of extraneous influences.

Starting with a physical definition of the boundaries of the study area, additional models are overlaid and interactions and interdependencies defined, to build the integrated model. These models relate to:

- the aquifer hydrological and salinity dynamics on a regular spatial grid
- the surface river hydrology with its topographically defined irregular spatial boundaries
- networks of intra and inter basin water transfers.
- the soil and slope hydrology defined using a regular grid within the catchments, and finally
- demographic influences using both regular spatial representations and predefined administrative regions.

Driving this suite of models are definitions of policy scenarios from which the emergent spatio-temporal dynamics of the system can be interpreted to facilitate redefinition of scenarios as required by the conceptual framework, accounting for the socio-cultural perspectives evident in the region.
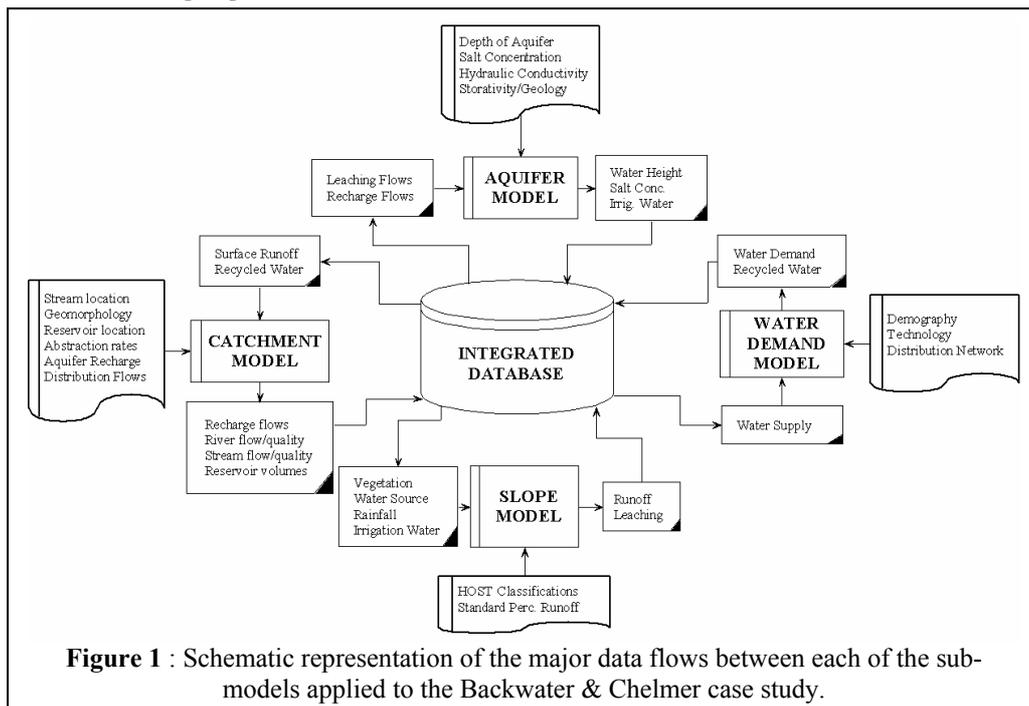
It is only possible here to summarise the models and the reader should refer to the cited literature for more detailed descriptions and for information concerning model calibration and validation [Oxley & Jeffrey 2001].

Figure 1 highlights the linkages between the models, in particular through runoff, leaching and recharge flows, and where abstraction from rivers, reservoirs and the aquifer provides the supply to the water demand model. It also shows the manner in which each individual sub-model has been allowed to retain an appropriate degree of autonomy within the modelling framework. Such an approach ensures that each model maintains its specific internal spatial definitions and timesteps, at the same time providing access to a shared database through the meta-level driver and user interface. Thus, the co-ordination of space and time (annual, daily and hourly changes) and the flow of data between the sub-models is facilitated by the driver, and the user interface provides an environment for the definition of policy scenarios.

2.1 Soil Hydrology

The model addresses hydrological dynamics relating to surface runoff, infiltration, leaching rates and sub-surface lateral flows based upon equations which have been adapted from work elsewhere addressing hydro-chemical interactions within the soil domain [Oxley & Allen 2000]. These hydrological dynamics provide the spatial contextualisation for the effects of vegetation density and changing soil water storage capacities.

Figure 1 : Schematic representation of the major data flows between each of the sub-models applied to the Backwater & Chelmer case study.

The model operates on a spatial resolution of 250m with a daily timestep.

The surface runoff and sub-surface lateral flows are both dependent upon the amount of surface water present:

$Runoff = (1 - \mu) * SPR * W_{Surf}$ (Eq. 1)
$Lateral = \mu * SPR * (W_{Surf} + \alpha * \beta * W_{Soil})$ (Eq. 2)

where: W_{Surf} & W_{Soil} = surface & soil water volume, SPR = the Standard Percentage Runoff, μ = the infiltration percentage, and, α and β are calibration parameters.

The Standard Percentage Runoff (SPR) used here is based upon the HOST (Hydrology Of Soil Types) classification system which categorises soil hydrological processes by defining the predominant flow paths through the soil [Boorman et al 1995]. It can provide an indication of the aggregate runoff characteristics for a given soil type, but is also affected by both vegetation cover and slope.

The vertical flows, involving infiltration from the surface and leaching from the soil water, can be defined by:

$Infiltrate = \mu * W_{Surf}$ (Eq. 3)
$Leaching = \lambda * \mu * W_{Surf}$ (Eq. 4)

where: λ inhibits leaching until the soil water is close to saturation.

2.2 River Flows

The Catchment model has been adapted from an earlier model of the Scheldt Estuary [Billen et al, 1990], which was spatialised in the Rhone Valley [Allen et al 1996], and has been adapted and applied to the Blackwater & Chelmer catchment, with additional dynamics implemented which address the transportation of water between catchments (using canals or pipelines) and further reaching distribution of water to urban areas, storage reservoirs, treatment plants etc. The model is based upon the concept of stream orders within a catchment and allows the simulation of linked sub-catchments within an overall watershed and operates on a daily timestep. The tributary flows are defined by:

$$Qaf_j = \left(Str_j - 2 \cdot Str_{j+1}\right) \cdot \frac{StrLen_n}{\sum\limits_{n}^{\max_n} StrLen_{j+1}} \cdot Delay_n\left(\frac{\Delta t_n}{2}\right)$$

(Eq. 5)

where, $Delay_n(t_n)$ is a function that makes a linear interpolation between $Q_{j,t}$ and $Q_{j,t-1}$ depending on a point in time, t_n, between both, and n = the stream order.

With all the tributary flows calculated these are summed together with the main river flows:

$$Q_{n,t} = In_n \cdot Area_n \cdot C_2 + \sum_{j=1}^{n-1} Qaf_j + 2 \cdot Delay_n\left(\Delta t_n\right)$$

(Eq. 6)

where, t_n = time discharge enters stream, n = stream order, Str_n = number of streams order n, $Area_n$ = catchment area of stream n (km^2), $StrLen_n$ = stream length (order n) (km), In_n = Incoming runoff flow to stream n (mm), $Q_{n,t}$ = discharge (order n) (m^3/s), Qaf_n = flows from tributaries (m^3/s), Δt_n = time of flow through stream, C_2 = Conversion constant (mm/km^2 to m^3).

This model addresses both the river water flows and quality across the simulated catchments. These flows and quality are determined by stream orders but are driven by surface runoff, itself determined by the rainfall/evapotranspiration balances in the soil hydrology model, spatial aggregations of agricultural nutrient inputs (nitrates and phosphates) and by the demography of the region which will influence the water quality depending upon the existence and effectiveness of water treatment plants.

2.3 Aquifer Dynamics

The aquifer model has a spatial resolution of 250m and a daily timestep. Linkages to the soil and river models are via leaching and recharge flows, respectively. The model operates upon a conceptual basis whereby instead of solving for the next steady state of pressure heads in the aquifer (on a monthly basis) it calculates the actual spatial flows each day and revises the resultant pressure heads accordingly. In this way external stresses can change daily, enabling it to address intermittent abstraction in individual cells as opposed to relying upon predefined monthly spatialised stresses. Thus, with identical mathematical equations being used, both the model reported here and alternative models such as Modflow should produce identical results, *ceteris paribus* [Oxley et al. 2002].

The model domain takes the form of a regular grid of cells, of specific size, with water heights and solute concentrations being calculated at the centres of cells, and volumetric flows being calculated at cell boundaries [Robinson 1999]. The model calculates the three-dimensional flows of water within the aquifer and generates new water heads based upon these flows. The numerical equations used are derived from Darcy's Law of flow through porous media and the equation of

continuity. Combining Darcy's Law (in three dimensions) and the water balance equation we have the non-linear Boussinesq equation:

$$\frac{\Delta}{\Delta x}(K_x \frac{\Delta h^2}{\Delta x}) + \frac{\Delta}{\Delta y}(K_y \frac{\Delta h^2}{\Delta y}) + \frac{\Delta}{\Delta z}(K_z \frac{\Delta h^2}{\Delta z})$$

$$= 2S_s \frac{\Delta h}{\Delta t} - 2R$$

(Eq.7)

where: K_{xyz} = Hydraulic Conductivity in 3 dimensions, h = water head, S_s = Storativity, and R = Recharge volume.

Solute transport is based upon a simple particle tracking routine, which traces the advection of solutes associated with the volumetric flows of water. The resulting mass transports are used to calculate the new salt concentrations.

2.4 Water Distribution

The water distribution matrix represents a mechanism through which the user can modify the water distribution dynamics using a variety of scenarios. The nine categories of nodes identified above each have a very distinct effect upon the dynamics of water management and distribution throughout the catchment:

i.   Subcatchments
ii. Storage Nodes
iii. External Supply
iv. Sewerage Nodes
v.   Water Treatment Plants
vi. Population Nodes
vii. External Population Nodes
viii. Boreholes
ix. Other External Nodes

The demand per head for each recycling 'mode' (i.e. none, in-house or regional) is input via a data file as the demand per head (in m³/day). Also required for this calculation is knowledge of the population zone and population density (based upon publicly available census data) and the recycling zones. The calculation of the demand per cell (D) can thus be defined by:

$D_{i,j} = Pop_{i,j} * Dhead(recyclevel_{i,j})$ (Eq. 8)

Given the demand per cell, the demand per population zone (DZ) can be calculated by:

$DZ_z = \Sigma D_{i,j}$ (Eq. 9)

Using the categories of nodes listed above to organise the distribution nodes, it is possible to define the water distribution matrix itself. In this example there are 50 individual nodes, and

relationships between the nodes (eg. water flows, transfer or demand) can be defined and modified in order to specify alternative distribution patterns. The complexity of the potential combinations (within the model) for distributing water from one location to another is clear from this matrix. In order to alter the distribution pattern the user has to modify this matrix and the model will then respond to the new definitions.

2.5 Strengths & limitations

The strengths and limitations of the modelling approach reported above are as follows:
- New infrastructure configurations and process nodes can be easily added to the catchment representation.
- Simulation links natural and imposed flows (e.g. rivers and pipes) and supports spatially variable consumer behaviour.
- Regional development options can be used in the simulations (population change, capacity expansion etc.)
- Simulations are complex to initialise and run
- Output is time consuming to analyse
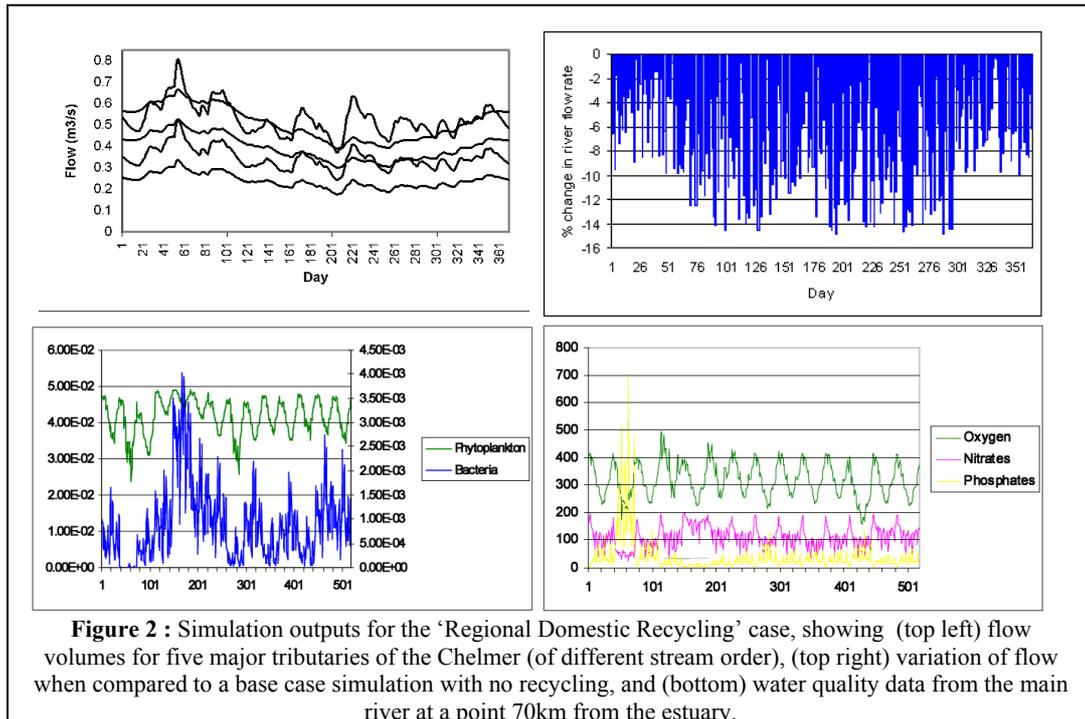- Water quality representations are simplistic

3.   REUSE SCENARIOS & SIMULATION

The primary objective of the modelling work was to simulate a variety of policy scenarios for water reuse at catchment scale. These scenarios are very complex owing to multiple, competing, water companies being responsible for potable water supply, waste water treatment, or both, with the boundaries of their activities conflicting with the natural boundaries of the catchment and the population distribution.

In order to explore the possible impacts of different water reuse schemes on the water quality and balances we describe four reuse scenarios reflecting major reuse options within the European water management environment.

3.1 Indirect potable recharge via augmentation

This scenario is inherently a property of the water distribution network and involves the use of treated wastewater from Chelmsford. This water is discharged into the river Chelmer and then re-abstracted and pre-treated further downstream and transferred to Hanningfield reservoir where it is stored prior to final treatment and distribution. Resources available at Hanningfield are thereby augmented using indirectly appropriated water from Chelmsford STW.

Figure 2 : Simulation outputs for the 'Regional Domestic Recycling' case, showing (top left) flow volumes for five major tributaries of the Chelmer (of different stream order), (top right) variation of flow when compared to a base case simulation with no recycling, and (bottom) water quality data from the main river at a point 70km from the estuary.

Specification of this scenario only requires a definition of the water imports in the distribution matrix. The integrated model then automatically propagates these flows through the system in response to water demand dynamics implemented within the model.

3.2 In-house recycling

This scenario represents a recycling activity operating at the micro scale. Individual households cannot be simulated as the model operates at a spatial resolution of 250m. Neither is it appropriate within this context to simulate the micro-level dynamics which emerge from the different recycling technologies employed.

Consequently, specification of this scenario is very straight forward. The observable effects of the micro-scale dynamics from the viewpoint of water resources is a reduction in the water demand from households. Thus, specification of this scenario either requires modifications of the distribution matrix to reduce the demand, or specification of the population zones affected and the average demand per person. In the latter case, the model automatically amends the distribution matrix by recalculating the demand from this average and the population density of the recycling zone.

3.3 Regional domestic recycling

Regional domestic recycling is an extension of the in-house scenario. The assumption underlying this scenario is that groups of households are able to collaborate at the multiple house, street, or neighbourhood scale to exploit opportunities presented by non-standard supply & demand pairings. For example, several houses could combine to provide greywater for centralised use in washing cars, or a neighbourhood could provide sub-potable water for a small industrial process.

3.4 Reuse for irrigation

Water reuse for irrigation purposes will reduce the demand for river water and aquifer abstractions by farmers. The simulation of this scenario can again be specified using the matrix. The mechanism for implementing this scenario is to take water from the selected waste water treatment works and distribute it to a specified sub-catchment (identifying stream order zero; i.e. no stream).

One further scenario, aquifer recharge, could not be simulated due to inadequate data for defining the aquifer structure and calibrating the internal flow dynamics. However, with these data becoming available, the model is structured to address aquifer recharge scenarios.

3.5 Results

Figure 2 shows representative output for a model run involving the 'regional recycling' scenario. The results suggest that river flow rates at specific points in the catchment are likely to be

significantly affected by regional scale recycling schemes as a large proportion of the flow in these basins comes from sewage treatment works.

Detailed simulations have been carried out to compare the impact of two types of water recycling regime ('in-house' and 'regional') applied to the same geographic space on river water flows, river water quality and water savings (as a function of reductions in inter-basin transfers). Table 1 presents summary results from these simulations.

Table 1: Summary results from simulations.

Measure	Impact of	
	In-house recycling	**Regional recycling**
River flows	No noticeable change	Localised changes
River water quality	No change	Slight deterioration
Inter-catchment water transfers	~18% reduction over 5 years	~12% reduction over 5 years

These results suggest that although regional recycling schemes are able to generate a greater variety of supply-demand functions (i.e. variety of reuse configurations), they are less effective as water saving measures than single house schemes.

4. CONCLUSIONS

In terms of options for water recycling in the Chelmer and Blackwater catchments, our investigations allow us to conclude that:

- Simulation modelling can be used to explore the impact of water recycling projects on water flows and quality at catchment scale.
- The particular configuration of abstractions, discharges and transfers found in the Blackwater & Chelmer catchments appear to provide a robust water management regime.
- The connectivity of the hydrological system in the Chelmer / Blackwater region provides a large degree of flexibility in the planning of water recycling schemes.
- Low to medium uptake rates of in-house water recycling devices (< 30%) are unlikely to have any significant impacts on catchment water balances (i.e. typically of the magnitude of normal yearly / seasonal variations)
- Regional schemes which do not transfer water across catchment boundaries have the potential to adversely influence hydrological flows and river water quality.

Finally, it should be remembered that the immense spatial and temporal complexity of the human-environmental interactions which have been integrated reflects an achievement in itself. However, it must *always* be recognised that there will be many omissions and assumptions involved in such work, necessitating the careful interpretation of any results within both the social and natural contexts to which the model has been applied. The use of such a modelling framework should only ever be for exploring (and learning from) potential futures, and never for precise quantifiable predictions of the future.

5. ACKNOWLEDGEMENTS

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