Taking account of water supply infrastructure in land-use planning: an integrated supply-demand approach

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Abstract: Demographic pressures have led the UK Government to embark upon a substantial programme of new housing development across the country, with particular emphasis on the south and south east of England where demand is greatest. The new developments will require careful planning in terms of their geographical location, timing and in terms of infrastructure, as the current water supply network in the south and south east of England is unlikely to be able to deliver adequate, reliable supplies to planned new developments without significant investment. How should the infrastructure be expanded to best meet changes in water demand from new housing? How should new housing be planned to minimise stress on existing infrastructure and reduce total investment costs? This paper presents a novel simulation tool, INFRAPLAN, developed to provide a means of exploring different demographic, land-use planning, water demand and infrastructure investment scenarios for a 49km x 59km region in south east England. INFRAPLAN integrates a cell-based land-use change model with a network-based hydraulic simulator and provides output which can be run through the built-in optimisation engine to determine the best (least cost, maximum performance) infrastructure expansion plan. The structure and operation of INFRAPLAN is described along with results from scenarios representing variations in demographic pressure, land-use plans and infrastructure expansion. The role of integrated assessment models such as INFRAPLAN are then discussed.

Keywords: water supply; new developments; integrated modelling; integrated assessment modelling; land and water planning

1. INTRODUCTION

Housing expansion in England and Wales has been on the political agenda since the late 1990s when the Office of the Deputy Prime Minister projected that an additional 3 million homes would be required by 2016 to relieve pressure on the housing market (ODPM 1999). Unfortunately the need for additional water supply infrastructure was not adequately taken into account when initial estimates for new housing were made. Without adequate and appropriate infrastructure capacity, water won't be delivered in the right quantity to the right places at the right times in response to changing demand patterns. Local authorities in the south east have estimated that a £30 billion investment in water supply and distribution infrastructure will be necessary in order to cope with the planned development (Lawrence 2004).

There are also concerns about water resources in the identified expansion areas. Water may need to be transferred from elsewhere in the UK via pipelines, new resources developed (e.g. reservoirs, desalination, rainwater harvesting etc.), current demand levels reduced or water use made more efficient through the use of technologies like water recycling. If not, then current and new housing stock may not receive reliable supplies of drinking water (Environment Agency 2004).

For obvious reasons, the key solution to avoiding water related problems during land-use planning is improved co-ordination between the relevant organisations involved. The planning systems for land and water in the UK have historically been relatively separate and it is recognised that communication difficulties have arisen as a consequence (Slater 1994, Carter *et al.* 2005).

The governance issues involved in improving co-ordination between land and water constitute a remit beyond that of this paper. Instead we shall focus here on the more modest aim of discussing the role of integrated assessment models (IAMs) as a means of providing information support to land and water planning organisations, using the UK housing expansion programme as an example.

IAMs have been recognised within the research community as having the potential to inform and support policy and planning activities (Parker *et al.* 2002, Jakeman & Letcher 2003), although a range of challenges have been identified to designing such models to be useful (McIntosh *et al.* 2005). This paper aims to describe and discuss a particular IAM called INFRAPLAN as a tool to support land and water planning co-ordination.

2. DESCRIPTION OF INFRAPLAN

2. 1 Purpose

The INFRAPLAN model was developed to address three main classes of question:

1. The impact of different water supply network expansion options on network performance and/or development plans being realised (i.e. houses to be built) (*aim - to identify optimal network expansion plans*).
2. The impact of different land-use change (land planning and demographic) scenarios on network performance and/or development plans being realised (*aim - to identify pathways for getting from current land-use to a planned future land-use*).
3. The impact of changing water demand levels for different land-use types on network performance and/or development plans being realised under a particular land-use change scenario and network expansion option (*aim - to better understand the impact of changes in water demand on water supply and regional development, and for identifying key demand management intervention options*).

The first two classes of questions will be addressed within this paper.

2.2 Overall structure

The structure of the INFRAPLAN model is depicted in Figure 1.

It consists of three sub-models, namely Land Use Change (LUC), Water Demand (WD) and Infrastructure (INF) linked sequentially in a chain to represent the direction of influence between each sub-model. The LUC sub-model consists of a process to simulate changes in land-use (LU) in response to planning and demographic scenarios, and water supply infrastructure capacity. The WD sub-model consists of a process to simulate domestic and non-domestic water demand based upon LU and a set of demand parameters. The INF sub-model consists of a Hydraulic Simulator (HS) and a Network Optimiser (NO).

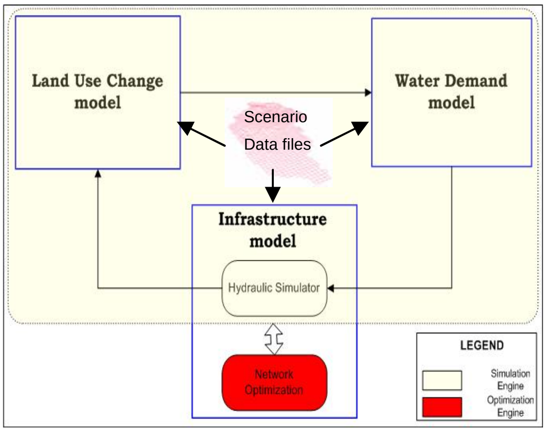

Figure 1. Structure of the INFRAPLAN model.

The whole model is driven by changes specified in scenario data files. INFRAPLAN is designed to explore the consequences of demographic (migration rates), land planning constraint (housing and other urban land-use types – where, when and how many) and network expansion (new pipes or trunk mains junction points) scenarios.

2.3 Temporal representation and operation

The planning horizon for INFRAPLAN was set to 30 years. The time step of both LUC and WD models was set equal to 1 year, finer resolution being deemed unnecessary.

Change in the water supply network was restricted to occurring only once every 5 years to reflect the five year planning process adhered to by all water companies under UK Government regulation. Consequently, a network expansion plan consists of six sequential sets of changes in topology and/or element characteristics e.g. pipe diameter.

Change in land planning constraints (e.g. where houses can and cannot be built, permissible housing densities etc.) can only occur every 10 years to reflect the 10 year regional structure planning process in England and Wales.

Table 1 lists the main INFRAPLAN temporal assumptions regarding the planning process.

Table 1. INFRAPLAN temporal assumptions.

Description	Value
Planning Horizon	30 years
Number of LU / WD / INF simulate cycles	30
Number of short term infrastructure cycles	6
Length of short term infrastructure cycles	5 years
Number of regional land planning cycles	3
Length of regional planning cycles	10 years

INFRAPLAN has an annual time-step, and runs for 30 time-steps per run. Every 5 time-steps the water supply network may change and every 10 time-steps the land-planning constraints may change. Migration rate can change every time-step.

Network expansion plan optimisation is performed separately from the main simulation, and uses the results from multiple runs to determine which plan is optimal (with respect to cost and performance) over a range of housing development scenarios.

2.4 Spatial representation and operation

INFRAPLAN was developed for and only applied to a particular region – the M11 corridor that stretches from London to Cambridge. The M11 corridor has been identified as a key expansion area for new housing by the UK Government (ODPM 2003). Water supply in the M11 corridor is controlled by a number of water companies and the modelled region represents an approximately 49km x 59km area of the M11 corridor supplied by one water company.

Within this region space is represented as both a grid of 100m x 100m (1ha) cells *and* a series of nodes linked into a network. The LUC and WD sub-models operate on the cellular grid representation of space whilst the INF sub-model operates on the node representation, where nodes represent junctions in the trunk mains network. There is a need for the INF sub-model to relate cellular WD to nodes and for the LUC sub-model to relate node pressure to cellular suitability for development (further detailed in next sub-section).

Nodes have spatial locations that are defined in terms of cells (row, column co-ordinates) with potentially more than one node per cell. All cells in the grid are allocated to the nearest 'supply' cell i.e. one which contains a node. If there is more than one node within a 'supply' cell, all cells allocated to the 'supply' cell in question are assumed to be 'equally' allocated to all nodes within it. This means that the summed WD of all the cells allocated to a 'supply' cell will either be expressed onto a single node (if the 'supply' cell only contains one) or expressed equally across all nodes (if the 'supply' cell contains many).

The supply network consists of two types of nodes: actual nodes and potential nodes. The former are nodes that are part of the real infrastructure at the beginning of the planning horizon (beginning of the simulation). The latter are nodes that can be potentially linked, as a result of expansion, to the existing network. Potential nodes will remain inactive unless on a 5-year expansion loop the infrastructure model links these nodes to the network based upon a scenario specification of when to activate potential nodes.

At the beginning of each 5-year period, each cell is allocated to the nearest cell with an active (i.e. actual) node. Depending on whether new nodes have become active this may entail re-allocation of cells from one 'supply' cell to another, to reflect changes in the structure of the supply network.

2.5 Land-Use Change sub-model

The LUC sub-model is designed to distribute annually specified population change across the modelled region in the form of changes to housing. Each cell is represented as being one of 19 possible LU types from 'natural' types such as agriculture and public green space through 'urban' types such as airport and light industrial to 5 different housing types. The initial LU type map was constructed from 100m x 100m Corine data.

All cells are also represented as either being 'allocated' (available for housing development) or 'designated' (not available for housing development). The allocated and designated cell maps can change every 10 years during a simulation to reflect changes in land plans. The initial designated map was constructed from land planning data provided by a UK-based town planning consultancy. The initial allocated maps used for scenario exploration were developed using a mixture of expert town planning knowledge regarding preferred urban development patterns, rates and sizes, combined with the major planning documents for the modelled region – the East of England Plan (EoEP - EERA 2004) and LUCS-20 (ODPM 2005). Planning constraints on the types and density of housing that can be built are represented using additional maps.

The location of 'non-housing urban' LU types like schools, retail etc. are pre-determined by the user of INFRAPLAN. Cells are selected to become schools etc. before a run and represented in a map of potential 'non-housing urban' LU types. During a run such cells remain in their initial state unless they become adjacent to one or more cells of any urban LU type, when they will change from initial state to the potential non-housing urban LU type.

Under conditions of immigration to the modelled region the population influx (no. of people) is distributed across the region as new housing cells. Cells have a suitability value calculated every time-step as a function of node pressure and distance, the assumption being made that cells allocated to nodes with low pressures and/or far away will be less attractive to housing developers as they are likely to incur greater supply connection costs. Pressure and distance (from nearest cell with a node) are weighted equally for the scenarios reported in section 3 but the weighting can be changed by the user, as can the shape of the functions relating these two variables to suitability. No attempt is made to incorporate any notion of urban centre in the model with no apparent behavioural consequences in terms of unrealistic urban growth patterns.

Allocated cells adjacent to existing urban LU type cells are ranked in order of suitability and then randomly tested to see whether they turn into new housing. If they do the population influx is decreased by a number equal to the density of houses for that cell multiplied by an average no. of occupants for the housing LU type in question. Housing type is randomly selected for a cell unless there are planning constraints.

Under conditions of emigration from the modelled region the population decrease is accommodated by turning housing cells adjacent to existing ‘brownfield’ (i.e. abandoned urban) LU type cells into new ‘brownfield’ sites. This occurs on a purely random basis across the region.

LUC changes according to these rules which are meant to (i) reflect the way in which land is built upon in UK (e.g. sequential expansion in an ‘onion’ skin like manner), and to (ii) provide a random allocation method for population change within the constraints set by the input maps. Both maps and rules were derived from interviews with UK town planning consultants. The rules of LUC do not represent individual demographic decisions regarding attractivity and accessibility or anything else – once land is available for housing the assumption is that, given sufficient water infrastructure and a net immigration, people will move into the area. In addition, although the input maps are case-study specific (M11 corridor), the rules used to model LUC were designed to be generic – to represent UK planning practice. This was a deliberate design decision as no demographic information was available to the research team. Random allocation within a set of rational and realistic constraints was viewed as a reasonable ‘minimum demographic assumption’ alternative. There may some benefit to including demographics more explicitly in the model, but whether the benefit justifies the additional development effort will depend on what the model is to be used for (see the discussion).

2.6 Water Demand sub-model

The WD sub-model operates simply to calculate the water demand of each cell. The number of houses in each housing LU type cell is updated during a run. Monthly peak daily water demand distributions for each housing LU type are used to randomly generate 12 peak daily values for each house in each cell (one value per month). These are summed to give a single demand value per cell.

For non-housing urban LU type cells single monthly peak daily water demand values are calculated by a similar process but using LU type specific normal distributions with specified means and standard deviations (modifiable between runs).

2.7 Infrastructure sub-model

The INF sub-model consists of 2 components - the Hydraulic Simulator (HS) and the Network Optimiser (NO). The role of the former is to provide a feedback mechanism between the availability of water and the quality of its provision, and the land use change and water demand spatial-temporal patterns. The latter implements an optimisation algorithm based on Evolutionary Computation (Bäck *et al*, 1997) that searches for the expansion plans that best perform according to a set of criteria based on cost and network pressure. The NO is not central INFRAPLAN operation so it will not be detailed.

The Hydraulic Simulator consists of three components. The first component is an interface between the NO engine and the package that performs the hydraulic simulation of the network. The interface decodes the representation of an expansion plan generated by the NO and converts it into the corresponding structural changes that the network undergoes over the planning horizon. The second component consists of a routine to update the ‘supply’ cells to which each cell is linked. This is then used to assign “grid cell water demand” to the appropriate network nodes and, conversely, to redistribute nodal pressure to the respective grid cells for the purposes of calculating cell suitability. The third component is a software package to perform the hydraulic simulation of the network. Amongst the various proprietary and free packages available, it was decided to use EPANET2.

At the beginning of every 5-year cycle, the network is modified by the first component according to the expansion plan generated by the NO. Then, the second component updates the allocation of every cell to a 'supply cell'. This updated allocation list is used to aggregate the water demand values and to load these aggregate values into the respective nodes. Once the aggregated water demands are assigned to all the nodes of the network, the third component initiates the hydraulic simulator (EPANET2) to compute the nodal pressures. These pressure values are then distributed back to the LUC model according to cell-'supply cell' relations.

3. SCENARIO ANALYSES

3.1 Scenario specification

A set of eighteen scenarios were developed to explore model sensitivity and generate substantive results. To ensure scenarios reflected actual plans the EoEP, statistics concerning LU change (ODPM 2005) and supplementary information provided by DLA (a UK town planning consultancy with experience of the M11) were used.

The EoEP specifies population growth to 2031 under two different assumptions, which were used to form two demographic scenarios:

- Short run migration – based upon recent migration average figures only (higher).
- Long run migration – based upon longer term historical migration average figures (lower).

In collaboration with DLA three scenarios were formulated to represent variations in location, timing and extent of planned land availability:

1. Full extent of all identified growth areas available from year 1 (i.e. supply of land > demographic demand).
2. Sequential release of land in all identified growth areas in equal ten year periods over the thirty year run period (i.e. supply of land ≤ demographic demand),.
3. Sequential release of identified growth areas from SW corner up to the NE with full extent of land available in each growth area as soon as released (i.e. supply of land ≤ demographic demand; available in different amounts at different places & times).

The results of the first LU scenario under short run migration assumptions was used as a baseline for a preliminary optimisation with the intent of identifying a small set of equally optimal expansion plans. From this, three expansion plans were selected and run under each demographic scenario for each of the three land availability options, giving a total of 18 scenarios to explore.

3.2 Scenario results

There is not enough space to fully discuss the scenario output but some key points can be made in relation to the questions posed in section 2.1:

1. Different water supply network expansion plans exert an effect on the rate, timing and location of new housing developments through altering the suitability of land in response to the activation of potential nodes or the upgrading of network capacity (pressure).
2. Different network expansion plans exert qualitatively different effects on average network pressure, and on the pressure of some individual nodes.
3. Demographic pressure directly determines the rate, but not location, of new housing development.
4. Demographic pressure also exerts an impact on average network pressure, and on the pressure for some individual nodes.
5. The rate, sequence and timing of land release for new housing exerts an impact on the location of housing across the region.
6. The rate, sequence and timing of land release exerts little impact on average network pressure (important for ensuring reliable supplies of water to houses, for leakage management and to prevent stagnation).

Figure 2 illustrates the difference in growth rate (no. of new housing cells per year over whole modelled region) that can occur depending on how the water supply network is expanded and how land is released for new housing. Peaks in growth rate occur immediately after the activation of a new node on the supply network or the release of new (and suitable) land. Troughs occur as land available and suitable (with regards infrastructure) for new housing decreases.

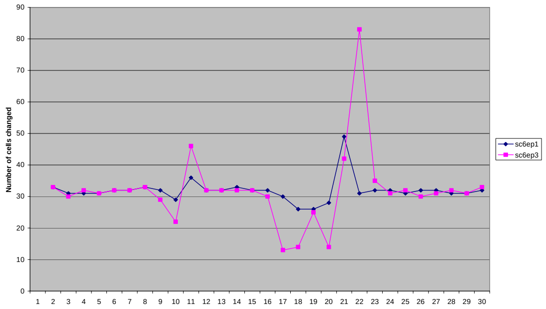

Figure 2. Housing growth rate for the M11 over time under two network expansion plans with the same demographic and land planning conditions.

4. DISCUSSION – THE USE OF IAMs IN LAND AND WATER PLANNING

So, having developed the INFRAPLAN model, one has to ask, of what use might it, as an example IAM, be and to whom? Following Van Daalen *et al.* (2002) it is clear that models can be used for a variety of purposes beyond that of directly informing a single organisational decision. Putting aside the debate as to whether single decisions exist as identifiable points (Langley *et al.* 1995), our experience of, and indeed aim in, developing INFRAPLAN was not to target a particular 'end-user' organisation with a specified decision to support. Although we worked with a particular water company we did not aim to produce a tool to be used directly outside the development team. This is in contrast to other examples of IAM development where claims are often made about the model being designed to be used by external organisations (McIntosh *et al.* in press).

The structure and operation of INFRAPLAN has been influenced by working with the water company, perhaps most obviously in that no attempt has been made to account for the wastewater network. The company in question has no responsibility for wastewater treatment – it is a 'water only' company. In not including the wastewater infrastructure the tool will clearly not give a complete picture of the relationship between infrastructure investment and land planning.

Is this a problem for the use of INFRAPLAN? Only if the tool is viewed as a means of identifying how 'best' to co-ordinate land and water planning. However, land and water planning in the UK are complex processes involving and influenced by many organisations, each with their own agendas, responsibilities and constraints e.g. the Government, the water regulator, the water companies, regional assemblies, local councils and housing developers. Given this institutional complexity we prefer to view INFRAPLAN as providing information to influence the structure of the planning process rather than providing recommendations on how best to operationally co-ordinate water supply investment & land planning.

From our research perspective, INFRAPLAN can be used to identify whether there are win-win co-ordination opportunities for water companies, land planning agencies and housing developers. Upgrading the mains network across a region based upon an understanding of likely land use changes over the next ten to thirty years could lower total investment costs compared to a piecemeal upgrading in response to the construction of housing developments one by one. This could in turn in lower the cost of each development, thereby improving the affordability of new homes and perhaps even increasing the likelihood of planned land actually being built upon by commercial developers. INFRAPLAN may be used to identify specific opportunities of this type or to provide evidence to support 'in principle' a move towards co-ordinated planning.

From the perspective of the water company, it may be useful to be able to point to research evidence (INFRAPLAN results) that show that investment costs can be reduced if the planning horizon is extended from the 5 year regulator imposed asset management planning cycle to 10, 15 or even 30 years. Such evidence may be useful in supporting lobbying to change regulation at the national level.

5. CONCLUSIONS

Having developed a sophisticated IAM it is important to also develop a sophisticated understanding of its potential uses. The authors experience with the INFRAPLAN tool is that the IAMs tend to play one of many possible roles from shaping agendas to providing evidence to support a plan of action. By their very nature IAMs tend to cross institutional boundaries and in doing so tend to address sets of issues that are not within the remit of any one organisation, and also do not fully take account of all the issues relevant to any particular organisation. In such cases we have found it more useful to develop IAMs to be used by researchers, with results for use by other parties.

Clearly the work reported here is incomplete. The incorporation of more detailed demographics may provide additional insight into how land-use plans are transformed (or not) into new housing with particular consequences for water demand. Sensitivity analyses would also be of benefit to gain a clearer picture of the feedback between water supply and water demand (through land-use and households).

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