An integrated cellular automata evolutionary-based approach for evaluating future scenarios and the expansion of urban drainage networks
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ABSTRACT
The paper describes and demonstrates an integrated cellular automata evolutionary-based approach for evaluating future scenarios including the expansion of urban drainage networks. The approach can be used to derive a drainage network layout based on future land use scenarios. Two techniques are used to derive the layout of the system: one using agent-based modelling and the other using similar principles built as a set of raster operations within ArcGIS. The tools and models are applied to a case study in Birmingham, UK. The results show that both techniques perform well for carrying out a scoping analysis at an urban scale. The case study shows that the application of the proposed approach for simulating urban growth processes and the consequent expansion of the drainage networks can achieve promising results. The interconnected drainage model for Birmingham shows that future developments will contribute further to flooding problems if no improvements are made to the existing drainage system. The same approach can be used to identify those drainage system elements that require immediate attention and which need to be replaced in order to improve the overall system performance.

Key words | city future planning, land use change modelling, network growth, urban drainage modelling

INTRODUCTION
Cities are complex systems in terms of their characteristics of emergence, self-similarity, self-organisation and the non-linear behaviour of land use changes with time (Batty & Longley 1994). Several techniques have been used to try to understand the city systems and infer patterns and mechanisms behind their dynamics. For example, Benenson (1998) used a combined approach of multi-agent systems and cellular automata (CA) to study population dynamics in a city; White & Engelen (1994) studied urban dynamics as a self-organising system using CA. More recently, techniques developed by other researchers based on CA have shown promising results, as such, the technique has been used to model different aspects of land use changes, including urban dynamics (Almeida et al. 2005; Engelen et al. 2007; Liu 2009; Soares-Filho et al. 2011). From the users’ perspective, this technique has several appealing features. The input data can be easily prepared in a GIS (geographic information system) environment using raster processing functions. The CA model can be coupled with GIS and the possibilities range from isolated to loose coupling to tight coupling to full integration. An integrated GIS-CA environment offers quick prototype creation and an attractive means of demonstration. All the results obtained from CA models can be easily presented and explored with GIS.

An approach to modelling cities has been described by Lechner et al. (2003). The so-called Cities Model is a multi-agent-based model which was developed in the framework of the project ‘Procedural modeling of cities’ at the Center for Connected Learning and Computer Based Modeling (http://ccl.northwestern.edu/cities/). This model allows a
user to create a terrain and environment in which a set of agents or ‘builder’ are used to create a city. There are separate agents, each functioning as a builder for a particular type of development, such as residential, commercial, industrial, or park. These agents move through the terrain, grouping patches of land into parcels they are responsible for, or increasing the size of the current buildings. Road builders move through the terrain building roads between the areas, thus increasing the value of the areas and their buildings (see for example Lechner et al. 2004). This agent-based model was developed in the Netlogo environment (Wilensky 1999). By linking the model with the game SimCity the authors were also able to generate artistic representations of urban landscapes.

Due to data limitations, some researchers have proposed the use of virtual or hypothetical case studies to evaluate different approaches or models. For example, Ghosh et al. (2006) propose a methodology to generate drainage networks artificially based on a dendritic Tokunaga fractal tree algorithm in ArcGIS (ANGel – Artificial Network Generator). Möderl et al. (2009) present a tool to generate an unlimited number of virtual sewer systems based on the Galton–Watson branching process. Sitzenfrei et al. (2010) describe a software tool (VIBe) that can be used to generate virtual urban water systems. Initially, VIBe generates a virtual environment including a digital elevation model (DEM), roads, buildings, water bodies and so on, and then writes input files for EPANET and EPA SWMM modelling systems to construct models for the water infrastructure.

To date, several case authors have reported successful applications of CA models to predict land use changes at catchment scale (Barredo et al. 2003; Van Delden et al. 2007; Kok & van Delden 2007). Their results have shown that the application of CA in modelling land use changes is feasible and that the outcomes of the models are similar to what is observed in reality. The Moland framework is an example of such a model that has been successfully applied and calibrated to real case studies in Europe (Barredo et al. 2005). Several other examples of CA models such as Dinamica EGO, SLEUTH and others have also been applied to different cities around the world, as presented by Clarke et al. (1997), Silva & Clarke (2002), Engelen et al. (2007), Liu (2009), Zhang et al. (2011) and Soares-Filho et al. (2011), among others.

This paper presents another new approach to derive the urban drainage network layout by connecting information on land use, topography and other urban infrastructure (e.g. roads). Once the key information from the existing urban system is extracted, the approach combines the use of a CA model of urban growth with an evolutionary optimisation algorithm to explore plausible future scenarios and to derive optimal drainage networks. Since the approach can be used to estimate the future drainage layouts by adopting a future land use map, the new system can be sized and connected to the existing system to evaluate the impact of future expansion on the aging existing infrastructure. This approach is tested on a case study in Birmingham (UK). The aim of the present research is to develop tools and methodologies that can be used by planners and decision-makers to analyse future scenarios and to foresee bottlenecks and possible rehabilitation strategies.

**METHODOLOGY**

The process of urban growth has an impact on land cover and the hydrological cycle, due to the use of materials in construction that increase the impermeable areas. Consequently, infiltration and recharge of groundwater generally decreases, while surface runoff volumes and peak flow rates increase. This situation calls for a proper provision of appropriate urban drainage networks. The effects of land use change on the rainfall–runoff process are relatively well understood and documented in the scientific literature, but the reliable estimation of runoff coefficients and parameters that govern runoff is still a challenging task.

The links between the spatial distribution of drainage and other features or characteristics of an urban area have been studied previously, for example, Mair et al. (2012) studied the similarities between roads, water distribution and sewer networks. The authors concluded that the water distribution network can be generated from the road network. Blumensaat et al. (2012) presented a method to derive a drainage network layout based on the manipulation of the DEM and the street network; data available on the Internet are used to estimate configuration parameters to build a drainage network model. The link between change in land use and change of urban drainage networks has
not been sufficiently studied or well documented. This may be due to the lack of appropriate historical records concerning the changes and/or construction done in the networks. Currently, there are many cities which have poor information on their existing drainage networks. It is often the case that the dimensions of pipes and ancillary structures and even their locations are not well documented. Given the continuous development of cities and their infrastructures, the proper management of the water infrastructure requires ongoing investments in terms of the man-power, time, methods and available technologies which can be employed to capture and manage the data effectively.

A regular issue in water infrastructure planning and management is how to extend the network to cope with the growth of new urbanised areas so that the impact on the existing infrastructure is kept to a minimum within an overall budget. Further, since almost every intervention in the existing drainage network may disrupt other urban services and networks, the extension of the drainage network requires careful analysis. One of the main concerns regarding the planning process is the unknown characteristics or state of the system in the future. The use of methods and tools such as agent-based models and CA for land use change can be used to understand the likely future changes in urban areas. These tools make use of spatial datasets that cover the urban area of interest.

**Data collection**

The application of the developed techniques requires a dataset that involves collection of data for land use/cover from at least two different years in order to determine the changes in different land use classes. Other datasets required include ancillary maps that provide data to explain the process of urbanisation or land use change, such as elevation, slope, boundaries, road network, or other services including gas, electricity and cable television, rivers, water bodies, etc. Depending on the availability of maps showing plans for future housing developments, business and industrial investments, and road expansion, these can be used to assess future scenarios.

Some of the constraints involved in using this modelling paradigm come from the limit on the amount of data required and the type of data. The implementation of satellite and remote sensing techniques has enhanced access to spatial information globally in recent years. Some issues still remain, for example the type of sensors used and the objective of the project are dependent on the time the information was captured and therefore influence the quality of the dataset. Also the classification of land cover/use for agriculture purposes differs from that used for urbanisation. In both cases the built-up area can be identified, but the land use within the built-up area requires ground-truth verification points, for instance, commercial and industrial areas.

Other issues relate to the fact that by using remote sensors the available datasets refer entirely to the physical world. In other words, it is possible to have information about the environment, boundaries and some infrastructure but it is not possible to map the decisions taken by political actors, decision makers, institutions, economists, the business market, etc., all of which can be important in setting the rules that drive urbanisation. The work presented here makes use of information and datasets that are currently freely available on the Internet together with other datasets that are acquired specifically for the case study.

For example, in the case of urban areas in Europe, land use maps can be obtained from the European Environmental Agency corresponding to the Corine Dataset. The dataset exists in different resolution for the years 1990, 2000 and 2006. Since the focus of the study is on urban areas a higher level of detail is considered necessary for artificial areas and therefore the Corine land use classes were regrouped into six classes mainly bringing together the agriculture areas, forests and pastures into a class referred to as ‘vacant land’. The other classes inside the urban agglomeration are: the continuous urban fabric which was renamed ‘residential 1’; the discontinuous urban fabric was renamed as ‘residential 2’; and the industrial/commercial fabric was kept the same together with recreational land use. Airports, water bodies and construction sites were separate Corine land use classes and were regrouped into a single class called ‘not modelled’. They were considered static classes in this study, that is, they did not change during the analysis.

Two different sources were used for the terrain data: Shuttle Radar Topography Mission (SRTM) data with 100 m resolution and ASTER Global Digital Elevation Model (ASTER GDEM) data with 50 m resolution. Both sources were used to match the resolution of the land uses acquired with the Corine Data. Both digital terrain model
(DTMs) were projected and used to generate the slope raster maps for 100 and 50 m resolution.

Other datasets representing the motorways, trunks, primary and secondary roads, rails, rivers, and canals were downloaded from the open street map project (http://www.openstreetmap.org/). Figure 1 presents the overall workflow of activities.

Models

Land use and spatial analysis

The question about how to derive the connection between land use and the existing urban drainage network is addressed in the present work. The existing urban drainage network at any moment in time is the result of a series of decisions made in the past. These decisions reflect the impact of design rules, policies, the economic budgets, and unplanned actions as a whole. The current state of the drainage infrastructure also reflects the level of knowledge and how advance the society is. In other words, is there a connection between land use and the drainage network apart of the estimation of runoff.

To address this question, we need to carry out a spatial analysis to see if there is a connection between the land use in an urban area and the properties of the urban drainage network.

The first step in this analysis was to focus on larger pipes, pipes with a diameter larger than 400 mm were selected from the drainage network layout. The second step consisted of the creation of ‘buffers’ or ‘rings’ around the pipes at every 100 m for a total distance of one kilometre. This task was conveniently done in ArcGis 9.3, and enabled us to explore the proximity of different land use classes to each pipe.

The area of each land use class in every ring was calculated leading to a knowledge of the distribution of land use classes along the main pipes. A similar analysis was carried out on the interception of the main pipes and with the land use classes using the zonal statistics analysis toolbox in ArcGis 9.3. This analysis produced a distribution of the length of pipeline that is intercepted for each land use class.

Layout generator

The development of an urban drainage network requires large investment by the community. Among the many factors that affect construction and operational costs are the diameters, installation depths, slopes, construction and operation of overflow structure and the use of pumping stations. As a basic principle, urban drainage networks are designed to follow the slopes of the natural terrain to make best use of gravity, and to minimise excavation costs and the use of lifting stations. The combination of these variables, the constraints imposed by the topography and the
size of the system make it hard to analyse it manually and computational tools are therefore required. The layout of a drainage network is required in order to size pipes and ancillary structures. Researchers have addressed this problem differently in the past; for example Li & Matthew (1990) proposed a discrete differential dynamic programming (DDDP) approach to find an optimal solution. In their approach an initial layout is given using the graph theoretical Dijkstra algorithm, and the pipes are then sized. After that the variables of the network are fixed and the layout is optimised using graph theory. The steps are repeated cyclically until the objective function does not change in comparison with a threshold value. A similar approach also using graph theory is described by Diogo & Graveto (2006), and Haghighi (2013). In this study we start the optimisation by deriving the initial layout which is then optimised in ArcGIS 9.3.

Approach 1: agent-based model

Agent-based models are often referred to as emerging paradigm models for which a population of autonomous agents interact to achieve a certain goal (see for example, Batty 1997). In the present work, an algorithm that simulates rainwater drops as agents was implemented in Netlogo; this is an agent-based platform (Wilensky 1999, 2006). The agent-based model needs the digital elevation data and the movement rules for the agents. The agents interact locally and will move to a lower elevation from their current locations. Each raindrop or agent has an elevation as a property. Several agents can be stacked one on another at the same location until there is a sufficient number of them to generate a positive gradient from the location to the nearest minimum neighbouring cell; in which case the agents move to the lower cell thereby tracing the trajectory or direction of flow. The agents are generated manually by the user using with the computer’s mouse at particular points of interest derived from the previous step in the buffer analysis. The points use the most interesting land use clusters to define the position of the main pipes in the drainage network. ‘Of interest’ are derived from the analysis done in the previous step, basically defining the most interesting land use clusters to position the main pipes of the drainage system. As a result of the simulation an image emerges forming the pattern that describes a flow path.

Approach 2: cost-weighted raster

The ‘cost-weighted raster’ model connects each of the generated attraction points in the drainage catchment formed in the study area with its outlet. Each link is treated as a straight line. The model creates a network layout taking into account the factors of land use, road alignments and terrain slope. The Euclidean distance between two points may be modified due to constraints that are the result of these factors. The constraints result in restrictions between certain cells and encourage connections to some other cell(s) of interest. Each link in the network must have a positive gradient. We also showed by a separate statistical analysis that the network should be aligned where possible with the primary and secondary roads. We also concluded that when extending the layout to new areas it may be cheaper to cross vacant land in order to have the shortest distance to the existing system.

This model was developed in Model Builder and Python Scripter. The model used the land use map simulated by the CA model, the DTM of 30 m resolution and the shape files of motorways and trunks, primary and secondary roads. The DTM was used to calculate the slope map of the study area.

The Hausdorff method for the distance between the generated layout and the existing system was used to measure the fitness of the generated layout. The Hausdorff distance is the longest distance between one set of polylines and another (Hangouet 1995)

Cellular automata

As mentioned above, the use of techniques based on CA has been growing over the past 10 years. One of the main
reasons for the growth of CA models is the development of remote sensing and GIS techniques that can easily be integrated with a CA model, facilitating the connection between several layers of information, visualisation, processing, and so on (Zhang et al. 2011).

CA can be described as a discrete dynamic system in which space is divided into regular spatial cells where time progresses in discrete steps. Each cell \( i \) \([i..N]\) is defined according to its position in the cellular grid and the size of the neighbourhood considered in the CA. Each cell has one of a finite number of states (i.e. land use classes). The state of each cell is updated according to local rules; that is, the state of a cell at a given time depends on its own state and the states of its neighbours at the previous time step. The CA models can include changes in both space and time (Hegde et al. 2005).

In this study, the Dinamica EGO software was used to simulate the urban dynamics (see Soares et al. 2011). DINAMICA employs, as input, a set of maps, including the initial and the final map of the land use, also known as landscape maps. Here a landscape can be viewed as a bi-dimensional array of land use types. Also included are two sets of ancillary maps for the static and dynamic variables; the latter are so named because they are updated at each model iteration. These two sets of variables control the location of changes in land use. The rules of the CA model are defined by the combination of the variables when calculating the so-called Weights of Evidences (Soares et al. 2011; Goodacre et al. 1993) to produce a transition probability map, which depicts the most favourable areas for change (see Soares-Filho et al. 2011, 2004, 2002). The validation of the outcome of the CA model consists of a comparison between model results and a reference map, in this case, the land use map at the end of the simulation. The fuzzy comparison method described by Hagen (2003) was adapted for use with Dinamica. The main task of Dinamica EGO is to analyse the evolution of land use classes. Once the model is calibrated it can be used as a tool to build future land use scenarios.

**Calibration of the CA**

Several applications were coded in Borland Delphi to read and update the specific components of the model. Following the recommendations given by the developers of Dinamica Ego (Soares et al. 2011), the initial weights of evidence matrix computed by the model was optimised within certain constraints. The best set was then used to optimise the parameters of the functions that account for the processes of urban dynamics, namely the expansion or contraction of the land use clusters. The names of these functions in Dinamica EGO are the ‘expander’ and the ‘patcher’. The change matrix is a type of communication function that calculates the number of cells to be changed between the ‘expander’ and the ‘patcher’. The evolutionary optimisation NSGA II algorithm was coupled with the Dinamica EGO model to handle the calibration process.

**Runoff extractor**

The runoff extractor is a tool that was developed by Medina (2012) to enable the user to select the study area and to download satellite imagery from Google maps API. The images are decomposed to red–green–blue (RGB) bands for which a supervised fuzzy classification is performed. The runoff extractor estimates the percentages of impervious and pervious areas (and their corresponding runoff coefficients) in a pixel-based calculation. This tool was tested and calibrated for the case study data (see Medina et al. 2012).

**Expansion of the drainage network**

The design of the conduits for the future expansion of the drainage network was carried out using the framework described by Vojinovic et al. (2008) and presented in more detail by Sanchez (2007) (see also Vojinovic et al. 2006). The framework consists of an evolutionary optimisation algorithm (NSGA II) coupled with SWMM that assesses the capital cost of the network as a function of the length and diameter of every pipe element and the estimated damage as a function of the volume of flooding. The cheapest solution generated in the multi-objective optimisation which produces no flooding is selected as the best option for design. Figure 2 presents the workflow of the optimisation approach.

Once the elements of the future expanded network are designed, they are connected to the existing network or model to assess the impact of the expansion on the existing...
infrastructure. The assessment is performed by considering the volume of flooding and its duration in the new scenario that is derived for the future land use changes.

**CASE STUDY**

The city of Birmingham is located in the West Midlands of England. The city has an area of 267.77 km². It has a population of 1,028,700 inhabitants according to the City Council estimate made in 2008 (Birmingham City Council 2012) and it forms a part of the larger West Midlands conurbation that includes other neighbouring towns such as Solihull, Wolverhampton and the towns of the Black Country. The West Midlands is the United Kingdom’s second most populous urban area with a population of 2,284,093 according to the census of 2001 (Birmingham City Council 2012). Industrial activity in the city has declined over the past 50 years. The economic

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**Figure 2** | Optimisation loop to design the expansion of the drainage system.

Construction Cost = \( L_i \times \sum C(D_i) \)

\[
\text{Damage} = \left( \sum \beta \times \text{Exp}\left(\frac{\text{FloodVolume}}{1000}\right) - 1 \right)
\]
crises in the 1980s caused a decrease in population that lasted until the year 2000. Since 2001 the city has experienced a rise in population as the rate of increase in population has been 4.2% between 2000 and 2010 (Birmingham City Council 2012).

Birmingham relies on a centrally managed water supply and wastewater/sewage collection service. It has privately operated water supply and drainage/sewerage networks both managed by Severn Trent Water (www.stwater.co.uk). Much of this infrastructure dates back to Birmingham’s industrial development during the 19th century, yet remains largely operational today (Darthe et al. 2008).

Population growth is leading to an increased demand for potable water and there is a corresponding increase in the flows and loads in the sewerage network and wastewater treatment plants. It is anticipated that the West Midlands population will increase by 6.6% between 2003 and 2023. This potentially poses a major problem for Birmingham because much of the area is drained by combined (stormwater and wastewater) collector systems and as such there will be an increased need to control runoff from rainfall events and attenuate localised flood risk (Last 2011).

Data collection

Land use maps for Birmingham corresponding to the Corine Dataset obtained from the European Environmental Agency and the Centre of Ecology and Hydrology (CEH) were acquired for the years 1990, 2000 and 2006 (Figure 3). Since the focus of the study is on urbanisation a higher level of detail was considered necessary for urban areas and the Corine land use classes were regrouped into six classes as described in the methodology above.

A visual inspection of the Corine maps revealed a significant change in the land use class ‘residential 1’ between the years 1990 and 2000. To verify this, the maps were compared against Landsat imagery for the same years. The analysis showed that the maps were reclassified using a different methodology. There was a need, therefore, to find another source of information that included more detailed data for the residential zone of Birmingham. For this reason, land use maps with a higher resolution (i.e., resolution of 30 m) were acquired from the CEH, UK (Morton et al. 2011). A detailed analysis of the sources of information was undertaken in Medina (2012).

A spatial dataset was collected for the study area. The dataset consisted of the following maps: DTM, derived slope map, main highways and motorways, primary and secondary roads, rail network, main rivers and canals, and the overland flow paths. Two different sources were used for the terrain data: SRTMdata with 100 m resolution and ASTER Global Digital Elevation Model (ASTER GDEM) data with 30 m resolution. Both DTMs were re-projected and clipped to fit the extent of the study area. The two DTMs

![Figure 3](https://iwaponline.com/jh/article-pdf/16/2/319/387271/319.pdf)
were used to generate slope raster maps for 100 and 30 m resolution.

The information regarding the urban drainage network was obtained through the SWITCH Learning Alliance established in Birmingham (www.switchurban.eu). The hydraulic model of urban drainage network used in this study was obtained from Severn Trent and it covers the Upper Rae Main catchment. Previous research done with this dataset has been reported by Thuy (2009) and Last (2011). An illustration of data used in the case study is given in Figure 4.

### Urban drainage model

The total urban drainage network for the city of Birmingham covers 27 catchments. A part of the network was used in the present case study including two catchments in the Upper Rae Main and Griffins Brook areas in the south west part of the city. The drainage model was originally built for InfoWorks CS. However for this study the data were adapted for EPA SWMM. As the conceptual framework of the two modelling systems is different it was necessary to adjust/calibrate the parameters of the SWMM model to fit the InfoWorks model. For this purpose, the InfoWorks model was assumed to be correct because it had been calibrated earlier against field measurements. The original model consisted of 2,796 sub-catchments and 6,340 conduits. Since the emphasis of the study was on how to expand the drainage network to include future developments, the model was pruned to decrease its complexity. The pruned network contained pipes with a diameter of 400 mm or larger. The layout of the pruned network is given in Figure 5. The pruned model contains 1,229 conduits and it was adjusted to reflect the characteristics of the full model.

### RESULTS

#### Land use and urban drainage system

As mentioned above, a corridor analysis was done along the main drainage pipes to derive a connection between the land use and the existing urban drainage network. The GIS layer with the buffers or corridors was then overlayed on the land use map for the year 2000. The outcome of this analysis is a distribution of the land use area per category that falls into each corridor. Figure 6 shows the result of the analysis for the land uses: ‘residential 1’, ‘industrial/commercial’, ‘parks’ and ‘recreational’.

Information obtained from the corridor analysis can be used to anticipate the location of new pipes in future scenarios based on the estimated land use. The land uses industrial/commercial and residential 1 show a significant change in the intercepted area at about 500 m. This means that the main collectors of the network are positioned within 500 m of these land use categories. It is possible that this finding reflects the traditional engineering practice of using a higher return period in the design and construction of drainage networks inside urban areas to provide a higher degree of safety to valuable parts of the city including governmental institutions, hospitals, industry, etc.

For the land use class ‘residential 2’, the analysis showed a homogeneous distribution of the area within the buffers, and therefore it does not provide valuable information about the location of the main drains.

A similar spatial analysis was carried out by overlaying the raster map of the land use for the year 2007 and the shape file containing pipes with diameter greater than or equal to 400 mm. Using a zonal statistical analysis method, it was possible to identify the total length of pipes for each land use (see Figure 7).

The results presented in Figures 6 and 7 give an indication of the spatial position of the main drainage pipes. In Figure 7, the land use class ‘Residential 2’ shows that a high percentage of pipes are intercepted. Also, by observing Figure 6 we can note that the ‘residential 2’ land use is homogeneously distributed in space. However, it does not provide information about the positioning of the main pipes. With this information rules can be defined to set up the behaviour of the agent-based algorithm to extend the drainage network.

Another important aspect of urban drainage is that the drainage is largely determined by the topography. In fact, this is the main criterion used for the design of urban drainage networks. Figure 8 presents a comparison between
the existing urban drainage network with pipe diameters larger than 400 mm in Birmingham and the derived natural drainage network obtained by processing the DTM. The flow accumulation map was used to derive the natural drainage.

Figure 8 shows a relatively high spatial correlation between the constructed drainage network and the GIS-derived natural drainage network produced for the terrain topography. The estimated spatial correlation using the fuzzy similarity comparison method of Hagen (2003) is 0.74.

The spatial analysis shows that it is possible to relate information from the land use map and the topography (elevation and/or slope) with the existing drainage infrastructure.
Deriving the network layout for the existing system

To test the approach an algorithm that simulates the dynamics of drops of rain was implemented in Netlogo. This agent-based platform uses the same digital elevation model and the points of interest according to the classification of land use and the corridor analysis discussed above. The points of interest were derived as the centroids of clusters with the land use (‘residential 1’ and ‘industrial/commercial’). The result of this simulation is a pattern that describes a flow path. Figure 9 shows the results of the simulation compared with the existing drainage network.

As can be observed from Figure 9 the algorithm simulating the dynamics of the rain drops can derive the layout of the existing main drainage network reasonably well. This shows that by combining the information on the land use (i.e., the points of interest) and the topography of the area a good approximation can be obtained for the layout of the main pipes of the network. Figure 9 also shows that some areas were not covered by the network. This is due to the fact that there are no land use clusters of interest in these areas and there is a need to find other key information in the dataset that can contribute to filling this gap.

Information regarding land use, topography, slope and the road network, was combined to create a cost-weighted raster in order to improve the layout generator. The cost-weighted raster is a map that contains a cost factor for each cell; the factor is used in combination with the start (new manholes) and end points (closest existing manhole) and the links between the attraction points. With this map it is possible to identify the least cost path (the one with the minimum total cost) from the starting point to the nearest manhole.
The creation of the drainage layout is achieved by crossing areas with gentle slopes, following the alignment of the existing roads and passing through ‘vacant land’, ‘residential 1’ and ‘industrial/commercial’ land uses. The outcome of the simulation for both cell resolutions (30 and 100 m) applied to the Upper Rae Main catchment is shown in Figure 10. This comparison of the results with the existing drainage system proves the validity of the method. Figure 10 shows that the layout approximates well to the layout formed by the main drainage pipes in the Upper Rae Main catchment. The Hausdorff method is used as a measure of fitness as indicated in the methodology. The results obtained are summarised in Table 1.

Figures 9 and 10, together with Table 1, show that the resolution of the raster used to predict the layout is important in the final result. A better spatial coverage of the drainage network is achieved when the resolution is increased. Some areas of the catchment are not covered by the simulated layout; this is likely to be due to the cell resolution, to a lack of information and/or to a limitation in the method. The outcome of the Hausdorff distance calculation shows that the maximum separation of the derived and existing networks is within 100 to 200 m range. While this indicator provides a measure of average proximity between the two layouts, there are significant differences in terms of the area that is covered and also in the direction of some of the line segments. This suggests that a different indicator needs to be formulated to assess the fitness of the derived layout. The range of separation calculated with the Hausdorff distance can be explained by the fact that the method is guided by the topography and tries to mimic the natural drainage paths, while in reality the existing manmade drainage system follows the topography and it is not necessarily constructed along the natural drainage network but adjacent to it. The use of the point of interest found with the corridor analysis can be even more valuable in zones with flat topography where the natural drainage flow paths are difficult to delineate.

When all the centroids of interest have been created and connected to the outfall of the catchment, they are then converted into segment lines and as such they represent the conduits or pipes in the urban drainage network. Similarly, the points created at both ends of the lines represent the manholes. One of the advantages of this approach is that all information is stored in a geo-database and this allows input files for the SWMM model to be created.

This approach can be further extended and used to derive the future layout of the network by using the land use change model as an input.

**Urban growth model**

The aim of this model is to facilitate the process of understanding the impacts of urbanisation in the case study area. Table 2 provides an indication of the main characteristics of this model.

In order to set up the urban growth model, all the collected datasets and maps were transformed into a raster format. The analysis was carried out using two urban
growth models with different resolution cell sizes. Additionally, the time span between the initial and the final year is also different for the two growth models. Model M1 has a cell resolution of 30 m and the initial and final land use maps correspond to the years 1990 and 2006, respectively. Model M2 has a cell resolution of 100 m and the initial and final land use maps correspond to the years 2000 and 2007, respectively. The two models were used to explore
the influence of the cell size and the time span on changes in the land use classes. Several experiments were conducted to calibrate the model. Details of the calibration can be found in Sanchez et al. (2012a, b).
The outcome of the calibration process is the set of parameters that closely resembles the final land use map. For model M1 the best achieved fitness was 62% and for model M2 it was 48.4%. The best set of parameters was then used as input to run the model for future land use change scenarios.

Running the model for a future scenario

The future scenario was calculated using the best parameters found in the calibration process. The model was run using the initial transition matrix computed for the years 2000–2006. The simulation was done until the year 2040. This means that for this scenario it is assumed that the demand for land per class had the same rate as during the years 2000–2006. Figure 11 shows the result of the simulation for model M2 (100 m cells).

Figure 11 shows the land use maps for the years 2006 (i.e., the initial land use map), 2015, 2030 and 2040. The maps show the expansion of the urban area and some infilling of vacant land within the main urban fabric by other land use classes such as recreational and industrial/commercial. Additionally, some new clusters of industrial/commercial land use were generated in different parts of the study area. Residential 2 (low density) is found to increase in area and there is a new cluster generated in the north corner of the study area. Residential 1 (high density) does not show any significant change. This land use class corresponds to the consolidated old city centre of the urban agglomeration and the model shows that there is no expansion or contraction of this core cluster, as such it compares well with the historical dynamics of this process.

Extending the drainage network layout to new developments

The method to derive the drainage network layout was tested with the existing network and it was used to generate the future layout of the network. This was done considering the land use changes generated by the urban growth model for the year 2040. Figure 12 shows the layout of the network considering the future land use map of the year 2040 for the model M1 and Figure 13 presents the result for the model M2 with a resolution of 100 m.

The generated layouts show that increasing the cell resolution is important to obtain a more detailed layout of the drainage network. Even though the land use model uses a different cell resolution, the spatial location of the likely future expansion of the drainage network is also the same. To assess the impact of the future land use change on the existing infrastructure, the layout produced with the land use model M1 is used for the purpose of design and interconnection.

Impacts of urbanisation on the existing infrastructure

In order to assess the impact of urbanisation on the existing urban drainage infrastructure, the future layout of the system was analysed. Knowing the spatial position of the future drainage layout, the ArcHydro tools were used to delineate the sub-catchment areas or areas that will naturally drain towards the drainage conduits. The sub-catchments were overlayed on the future land use map for the year 2040 to obtain the distribution of land uses. The runoff extractor tool was then used to estimate the percentage of pervious and impervious surfaces. Figures 14 and 15 show the surcharged nodes map for the pruned existing system and the expanded model considering the new developments. Both models were run for a recorded event with a return period of 2 years and 60 min duration.

The total area with new developments is 683 Ha and is distributed over 32 sub-catchments. The average percentage

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
<td>100 and 30 m focus is on the urban sub-catchments.</td>
</tr>
<tr>
<td>Set of states (cells)</td>
<td>Industrial, commercial, residential (2 subcategories), vacant land.</td>
</tr>
<tr>
<td>Transition rules</td>
<td>Probability functions.</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>Year (visioning, scenario planning and assessment).</td>
</tr>
<tr>
<td>Initial conditions</td>
<td>Derived from maps at a given year (1990, 2000, 2006).</td>
</tr>
<tr>
<td>Study area</td>
<td>Birmingham, UK.</td>
</tr>
</tbody>
</table>
Figure 11 | Simulated land use map for the year 2040 with model M2 (100 m cell).
impervious surface is 0.17% and the estimated average values of the manning n-impervious and n-pervious are 0.002 and 0.38, respectively. The estimated total runoff contribution of the new developments is 20,940 m³. Table 3 presents some indicators to assess the performance of each system.

Figures 14 and 15 together with the values presented in Table 3 show that the expansion of the drainage network will increase the total number of locations with flooding to 50 nodes or manholes. Part of the new developments is likely to occur in the area where the system is already in a critical condition (i.e., does not have sufficient capacity) which is highlighted by the total volume of flooding increasing to almost double its original value while the total duration of the flooding does not change significantly. Out of the total volume of runoff that is generated in the new developments (20,940 m³), a great portion (16,906 m³) will not be conveyed by the pipe system and will exacerbate the potential flood-related problems. This can also be observed in Figure 16 which shows the peak flow at the outfall of the system. The outfall is at the entrance to the wastewater treatment facility.

Figure 16 shows that a significant change in the flow at the outfall pipe for the tail of the event. This shows that it will take longer to reach the average operational condition of the treatment facility. This has implications for the operation of the system as the volume of tanks in the Wastewater Treatment Plant needs to be carefully considered and analysed against CSO (combine sewer overflow) frequencies and volumes in the future.

The total number of surcharged pipes does not change significantly considering the scenario for the year 2040. Table 3 shows that 360 pipes are surcharged in the system. Surcharge is the ratio of the maximum peak flow for this particular event and the full flow capacity of each pipe. This also identifies those pipes in the network that have pressurised flow conditions. Out
Figure 13 | Expansion of the drainage system for scenario 2040, model M2 (100 m cell).

Figure 14 | Surcharged nodes map for the pruned existing system.
of all the surcharged pipes, those elements with the largest change (i.e., pipes for which the increase in surcharge capacity is greater than 0.5) were identified. These pipes are presented in Table 4.

The identification of these critical conduits is useful information that can be used to evaluate potential rehabilitation strategies for the system. This again can be undertaken as a dynamic optimisation problem (see for example, Sanchez 2007 and Vojinovic et al. 2006).

**CONCLUSION**

This paper presents the results of research to develop an integrated approach for urban water systems analysis that
can be used as a planning tool to evaluate future scenarios in urban areas. Traditionally this type of analysis is done using different tools in a fragmented manner.

The method presented in this paper demonstrates that connecting the distribution of land use in an urban area with other urban infrastructure information such as roads, canals, and drainage networks can yield valuable information that can be used to derive the key rules relating the different factors and to obtain a good approximation of the drainage network layout. Two techniques were used to derive the layout of the system, one using agent-based models and the other one using similar tools to build as a set of raster operations within ArcGIS. The approach was tested on a catchment in Birmingham, UK. The results show that both techniques performed well for a scoping analysis at an urban scale level to derive the main pipes of the drainage network. As anticipated, the quality of the information affects both techniques. In particular, it was found that the cell size of the elevation map plays a major role.

In the case study area it was found that the main collectors of wastewater pipes are located within 500 m of the land use classes ‘residential 1’ (continuous urban fabric) and ‘industrial/commercial’. These are the main land use classes that influence the location of pipes in future scenarios.

The case study results show that the application of a CA technique for simulating urban growth processes can yield promising results. The spatial analysis identified the need to model the internal changes in the city land use and not only the expansion or contraction of the urban core. The development of the case study encountered several limitations regarding the nature and quality of the information needed to set up the model. The calibration process of the CA model was undertaken despite the fact that not all the variables that are involved in the urbanisation phenomena were used. The work performed highlights the need for a more multidisciplinary analysis.

To visualise the impacts of future urbanisation growth on the existing drainage infrastructure, the output map of the CA model for the year 2040 was used to derive a possible layout of the system in the future. The possible expansions of the drainage network were designed on the basis of the future land use map. The catchment parameters needed for the rainfall–runoff were estimated with the runoff extractor. The pipes were sized using the NSGA II algorithm coupled with SWMM within an optimisation loop. The new pieces of the drainage network were then interconnected to the existing model of the drainage system to assess its new performance and to evaluate the consequences of the future land use changes for the existing infrastructure.

The interconnected model for the future urban growth scenario of Birmingham shows that the future developments will contribute further to the flooding problem if no improvements are made to the existing drainage system. The total number of flooded manholes will increase by 50 and most of the runoff volume that will be generated by the new developments will exacerbate the flood-related problems due to the lack of hydraulic capacity of the existing system. The approach presented in this paper can also be used to identify the critical

<table>
<thead>
<tr>
<th>Priority pipes</th>
<th>Pruned existing system</th>
<th>Pruned extended system</th>
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<tbody>
<tr>
<td>Pipe 1</td>
<td>954.54 2.16 1.59</td>
<td>1,392.02 3.15 2.31 0.72</td>
</tr>
<tr>
<td>Pipe 2</td>
<td>984.11 2.23 1.67</td>
<td>1,301.91 2.95 2.21 0.54</td>
</tr>
<tr>
<td>Pipe 3</td>
<td>1,165.85 1.83 1.73</td>
<td>3,296.98 5.18 4.9 3.17</td>
</tr>
<tr>
<td>Pipe 4</td>
<td>2,189.67 4.96 1.73</td>
<td>3,006.31 6.8 2.37 0.64</td>
</tr>
<tr>
<td>Pipe 5</td>
<td>667.4 1.44 0.89</td>
<td>1,165.91 1.56 1.55 0.66</td>
</tr>
<tr>
<td>Pipe 6</td>
<td>55.57 1.44 1.58</td>
<td>92.12 2.32 2.61 1.03</td>
</tr>
</tbody>
</table>
pipes that require immediate attention for rehabilitation purposes. The same approach can be used to evaluate rehabilitation strategies to improve the performance of the system now and in the future.

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REFERENCES


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