Modelling the future impacts of urban spatial planning on the viability of alternative water supply

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ABSTRACT

Greywater recycling and rainwater harvesting have the potential to increase the resilience of water management and reduce the need for investment in conventional water supply schemes. However, their water-savings would partly depend on the location and built-form of urban development and hence its household sizes and rainwater per dwelling. We have therefore tested how spatial planning options would affect the future viability of alternative water supply in the Greater South East of England. Our integrated modelling framework, for the first time, forecasts the future densities and variability of built-form to provide inputs to the modelling of alternative water supply. We show that using projections of the existing housing stock would have been unsound, and that using standard dwelling types and household sizes would have substantially overestimated the water-savings, by not fully representing how the variability in dwelling dimensions and household-sizes would affect the cost effectiveness of these systems. We compare the spatial planning trend over a 30 year period with either compaction at higher densities within existing urban boundaries, or market-led more dispersed development. We show how the viability of alternative water supply would differ between these three spatial planning options. The water-savings of rainwater harvesting would vary greatly at a regional scale depending on residential densities and rainfall. Greywater recycling would be less affected by spatial planning but would have a finer balance between system costs and water-savings and its feasibility would vary locally depending on household sizes and water efficiency. The sensitivity of the water savings to differences in rainfall and water prices would vary with residential density. The findings suggest that forecasts of residential densities, rainfall and the water price could be used in conjunction with more detailed local studies to indicate how spatial planning would affect the future water saving potential of alternative water supply.

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1. Introduction

Future water shortages are expected in many parts of the world due to climate change and increasing population and incomes (Alcamo et al., 2007). The Greater South East of England already has seriously water-stressed areas (Environment Agency, 2013) and the frequency of droughts is projected to increase (Met Office, 2011). This has led to increased interest in developing plans for water resource management that are resilient in the face of urbanisation and climate change (DEFRA, 2016). Current linear urban water management practices require a transition to more circular urban water management (Butler et al., 2011) with reduced import of water; high rates of recycling; and reduced export of wastewater and stormwater. Alternative sources of water supply such as grey-water recycling (GWR) and rainwater harvesting (RWH) could have a role to play in this transition.

The UK water companies are required to produce Water Resources Management Plans that look ahead 25 years taking into account climate change and population growth and consider options for bulk water transfers between water company areas (Environment Agency et al., 2012). Alternative water supply (AWS) at the building-scale may therefore be beneficial if this helps to generate a surplus that could be redistributed to reduce the need for major investments such as reservoirs.

Conventional water supply in most countries is subsidised through supportive measures for large projects. Analogous subsidy

measures should be considered for AWS for appropriate comparative analysis (Campisano et al., 2017) and its financial benefits on a regional scale may be much more significant than the benefit to the individual consumer (Friedler and Hadari, 2006). Although there has been a reasonable uptake of AWS for commercial and public buildings, the uptake for residential buildings is low. This is probably due to the multiplicity of stakeholders, such as planners, developers, owners and occupiers, and uncertainties about its cost effectiveness and acceptability to households. Domestic water demand is a substantial and growing proportion of water consumption. Therefore understanding the long term potential of AWS for dwellings would be a useful step towards a whole system assessment of water management plans. Decisions on the provision of policy support would require a long term perspective because the rate of introduction of AWS could only be relatively slow. New-build in the UK only adds around 1% per year to the housing stock and the retrofitting of existing dwellings would probably only occur when convenient, such as during refurbishment.

The water-savings and costs of AWS systems depend on regional-scale factors, such as rainfall and water prices. They also depend on factors that vary from dwelling to dwelling, such as water consumption per person, household-size and roof area (Morales-Pinzón et al., 2015). Previous modelling of AWS has been either for specific dwellings (Friedler and Hadari, 2006) or existing areas using dwelling typologies (Kim and Furumai, 2012; Palla et al., 2012). However, household-sizes and roof areas vary with residential density and new build in the future will be different from the past. Spatial planning constrains the release of land for urban development, and hence the location and density of dwellings, as evidenced by comparing London, which is constrained within a green-belt, with the sprawl of some North American cities or the ribbons of urbanisation in Flanders. The demand for residential land is generally greater in areas with good access to jobs and amenities and, if demand exceeds supply, housing will tend to increase in density over time. Hence, the demand for housing changes spatially as a result of population growth, socio-economic transformation and transport improvements. Forecasting urban development therefore requires a model (Von Thünen, 1826) and cannot be estimated simply by projections from the existing housing-stock.

Mitchell et al. (2001) recognised the need for integration between built-form and households when modelling catchment water cycles. Existing dwellings were represented in their Aqua-cycle model as 'blocks', and groups of dwellings as 'clusters'. Models have since been developed for testing urban water management options, such as UWOT (Makropoulos et al., 2008). Kim and Furumai (2012) used five building types to model RWH options for an existing residential district and found that half of the water-savings would be for dwellings, far exceeding any other building type. Their analysis did not consider cost effectiveness, possibly because in Japan about half of the installation cost would be subsidised by local government. Thames Water (2017) considered the feasibility and costs of AWS for planned housing developments, but only tested AWS for two dwelling types (low-rise or high-rise) each with an assumed household size. The SWITCH project used 49 unit-blocks for characterising existing land use (Mackay and Last, 2010) but only 8 were residential and they were not designed for modelling future development. The main limitation of the above studies is that they rely on inputs of urban growth, densities and households.

A number of studies have used urban models for testing urban water management scenarios (Urich and Rauch, 2014a). These have mostly used cellular automata models for the bottom-up dynamic simulation of the urban development process. Urich and Rauch (2014b) combined a cellular automata model (described in Sitzenfrei et al., 2013) with drainage modelling. They simulated a range of urban development scenarios and found that spatial planning policy would be one of the factors that would affect flood risk. The limitations of cellular automata models are that they are based on transition rules specified by the user and they require inputs of urban growth. They do not model the location choice of firms and households and so they are unsuitable for modelling radical changes in regional spatial planning and transport policies. Willuweit and O'Sullivan (2013) used the MOLAND model. This included a macro-level system dynamics model to spatially allocate regional development but only for the trend, which was then represented by cellular automata modelling to provide inputs to a water-balance model. This used 4 hectare grid-cells but without details of the dwellings and households and GWR and RWH were included but based on user inputs of assumed capacities and percentage uptakes. This lack of detail means that the AWS water-savings were estimated rather than modelled. Polebitski et al. (2011) coupled a water demand model with the UrbanSim model (Waddell et al., 2010) to forecast regional domestic water demand. UrbanSim does include the behavioural choice modelling of land use and transport but it dynamically explores the urban development processes using numerous micro-simulations and this would have unnecessarily complicated our research.

The above models have used either grid-cell or parcel-based representations of neighbourhood layouts where each grid-cell or parcel is represented by buildings and floor space for a typical development type. For example, UrbanSim used 2.25 ha grid cells, and more recently parcels, with typically 25 development types of which 8 are residential and 8 mixed-use. However, this leads to difficulties matching and reconciling data sources such as allocating census tract household data to the residential floor space of individual parcels, or matching map data with model outputs (Abraham et al., 2005).

We have chosen to use a land use and transport interaction (LUTI) model that includes behavioural choice modelling and converges to a partial equilibrium for a given forecast year (Echenique et al., 2013). This type of model is well established in practice for testing spatial planning options and produces stable forecasts for testing the AWS scenarios (for reviews of urban modelling, see Hensher et al., 2004). We use an innovative statistical method of converting the forecasts of the LUTI model into an abstract representation of the housing stock and land use with sufficient detail to test AWS systems for individual dwellings (Hargreaves, 2015).

The findings presented in this paper are the outcome of multi-disciplinary research that has for the first time developed an integrated modelling framework to test how regional spatial planning would affect the potential of building-scale water technologies. Water companies have expressed a strong interest in using this type of model as a collaborative planning tool for constructive engagement with planning authorities on high-level scenario analysis. It could enable focused optioneering on the spatial supply and demand for water, depending on where land is likely to be developed, its density and land use types. Government agencies have also recognised the value of an integrated modelling tool to test the sustainability of options at an early stage of the planning process and the East of England Regional Development Agency supported this objective by funding the development of the state-of-the-art LUTI model that we used for our research. Our modelling framework could easily be enhanced to encompass all aspects of water management related to spatial development. However, for clarity and conciseness we demonstrate its capabilities by testing GWR and RWH scenarios.

The modelling is an aid to understanding how interactions between the relevant factors would affect future outcomes, rather

than attempting to forecast actual water-savings. We therefore exclude some variables, unrelated to spatial planning, that would have made our findings more opaque because of their differing effects on the uptake of AWS, such as its acceptability to developers and households. We show how spatial planning options would affect the future viability of AWS systems and the importance of researching this within an urban modelling framework.

2. Materials and methods

2.1. Research context

2.1.1. The study area

The Greater South East of England has a population of over 20 million (ONS, 2014) consisting of London and its surrounding regions. The urban areas are quite compact due to planning constraints such as local plans, green belts and areas of outstanding natural beauty to protect green space from urban sprawl. We chose electoral wards as the most appropriate level of spatial detail for the urban modelling because these are the smallest areas that had all the planning data needed for carrying out the research. There are 3,218 wards in the Greater South East ranging in size from around 220 to 23,000 people with average population of 7,040. Fig. 1a shows their average densities in year 2001 as dwellings per hectare of residential land (dph). Fig. 1b shows that the average household size per ward varies greatly, with smaller households in the remote areas and some high density areas (see Appendix A1.1 of the Supplementary Materials for further details).

2.1.2. Forecast period

We have tested scenarios for a forecast year of 2031. This is the furthest point in the future for which sufficient information existed about local planning policies. A base year of 2001 was chosen because this had the most complete dataset at the time of carrying out the research. This 30 year period allows a sufficient amount of demographic and socioeconomic change for clear differences to emerge between the base year and the forecast year. The population was projected to increase from 8.8 million in 2001 to around 12.1 million in 2031.

2.2. Research inputs

2.2.1. Future availability of residential land in urban areas

We have used household projections from the UK National Trip End Model (DfT, 2009) and density targets from the Local Development Frameworks of the local authorities. We have combined these densities and additional households to estimate how much land the local authorities expect to become available within urban boundaries over the forecast period, (such as by redeveloping industrial sites). Land outside urban boundaries is estimated from GIS data on land use and protected areas. We refer to dwellings that existed in the base year and would still exist in the forecast year as 'Existing' and those that would be built during the forecast period as 'New-build'.

2.2.2. Water consumption

We collected data from the Water Resources Management Plans (Environment Agency et al., 2012) of the relevant water companies for each 'Water Resource Zone' (WRZ). A 'WRZ' is the largest possible zone in which all resources can be shared and in which all customers will experience the same risk of supply failure from a resource shortfall. There are 49 WRZs in the Greater South East and they range from a few hundred to over 3 million households. This data includes the micro-components of water use for metered and unmetered households (toilet flushing, clothes washing, outdoor use, bathroom washbasins, showers, baths, dishwashing, and
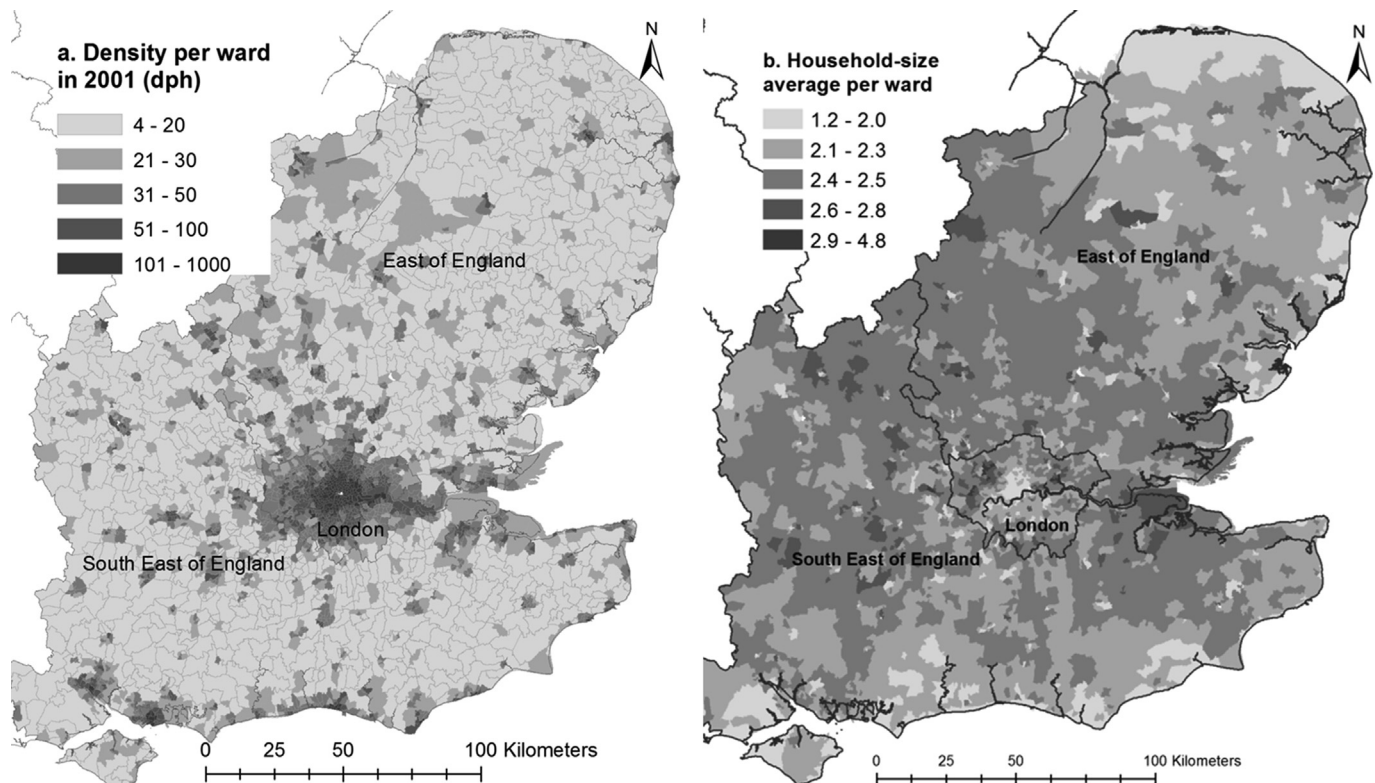

Fig. 1. Average residential density (a); and average household size (b) per ward.

miscellaneous) both for recent years and projections for the forecast year in litres per person per day (l/p/d). Fig. 2 uses toilet flushing as an example to show that projected water consumption varies considerably within the study area (toilet flushing is around 20% of total domestic water use). We assume each ward would have the same water consumption per person as the WRZ within which it lies (see Appendix A1.2.2).

2.2.3. Rainfall

We have used annual average rainfall and number of wet days (Appendix A1.1) for the period 1981 to 2010 (Met Office, 2011) and there are marked differences in rainfall with the east being generally drier than the west. We assume that the rainfall per ward is the same as the nearest weather station (Fig. 3).

2.3. The integrated modelling framework

The flow chart in Fig. 4 illustrates our integrated modelling framework. The remainder of Section 2 describes its components and scenario design inputs. The spatial scales of the inputs, models and outputs are summarised in Table 1.

2.3.1. LUTI model

The 'LUTI model' forecasts the spatial allocation of employment, households and population. It had been calibrated for the base year so that its outputs per zone matched the base year data. The inputs included industrial consumption and production per sector, employment, households and population by socio-economic classification, residential and non-domestic land, floor-space, property prices and transport network times, costs and capacities. The model endogenously generates rents to balance demand and supply using an iterative procedure. This includes not only quantitative aspects of utility, such as cost and time, but also qualitative aspects such as what consumers of land are willing to tolerate in order to have a lower monetary rent, for example, living in a high-rise building.
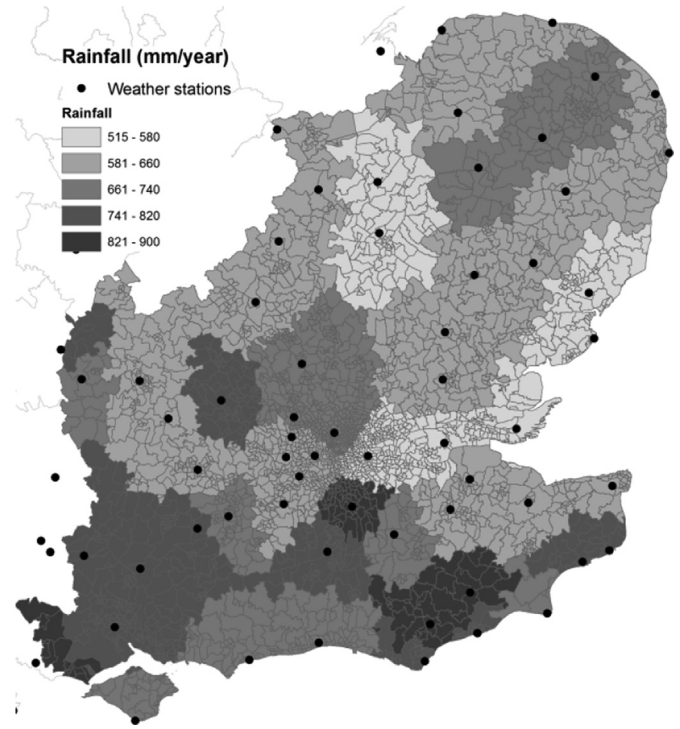
Fig. 3. Estimates of annual average rainfall per ward.

Projections had been input to the model of the land available for development and transport capacities. A forecast had been produced for year 2011, for validation purposes, and also for the 2031 forecast year. The model calibration and data sources are described in Echenique et al. (2013).

2.3.2. Tiles model

The average residential densities per ward from the LUTI model are systematically converted into 'tiles' to represent the dwellings and associated residential land. Each tile represents one hectare of residential land occupied by dwellings of predefined dimensions and plot size. We chose to use 20 tile types, as shown in Fig. 5.

The tiles act as a database of the housing stock and residential land use. There are two versions of each tile type to represent either Existing dwellings or New-Build dwellings. The 'tiles model' had been calibrated using English Housing Survey (CLG, 2009), census and GIS data (DCLG, 2005) to deterministically produce the expected frequency distribution of plot size per dwelling type (found to be a gamma distribution) for any given average density and age of dwellings. It then systematically selects a set of tiles to approximate this frequency distribution. This includes whole and fractions of tiles so that the summing of all the tiles matches the residential land and dwellings per ward, as forecast by the LUTI model (see Appendix A1.4 for further details). The method, calibration and validation are described in Hargreaves (2015). These discrete tiles are useful as a shared medium for multidisciplinary research (Hargreaves et al., 2017).

This simultaneous matching of the land, dwellings and variability of their plot-sizes would have been very difficult to achieve if using a land-parcel or grid-cell method. The tiles method can achieve this because the tiles are an abstract representation of the land use and dwellings without being constrained to match a predesigned layout (simulating the future layout of residential areas is unnecessary for testing AWS systems for individual buildings).
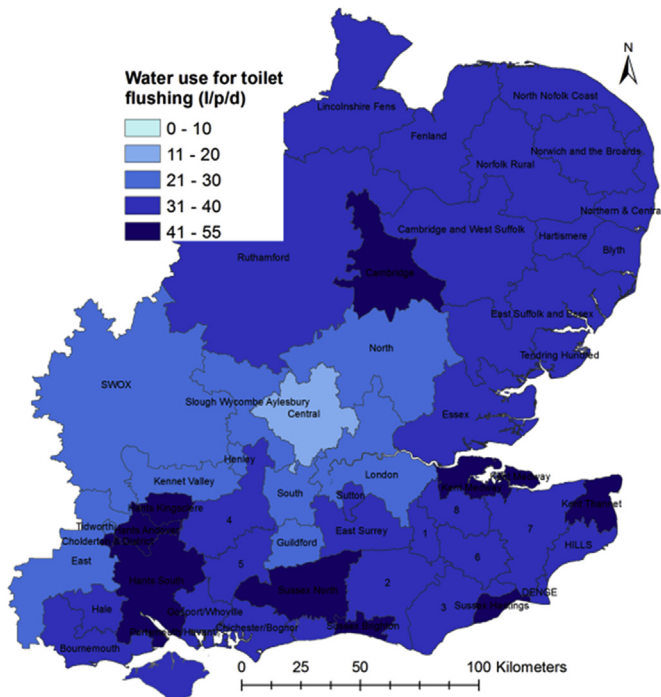
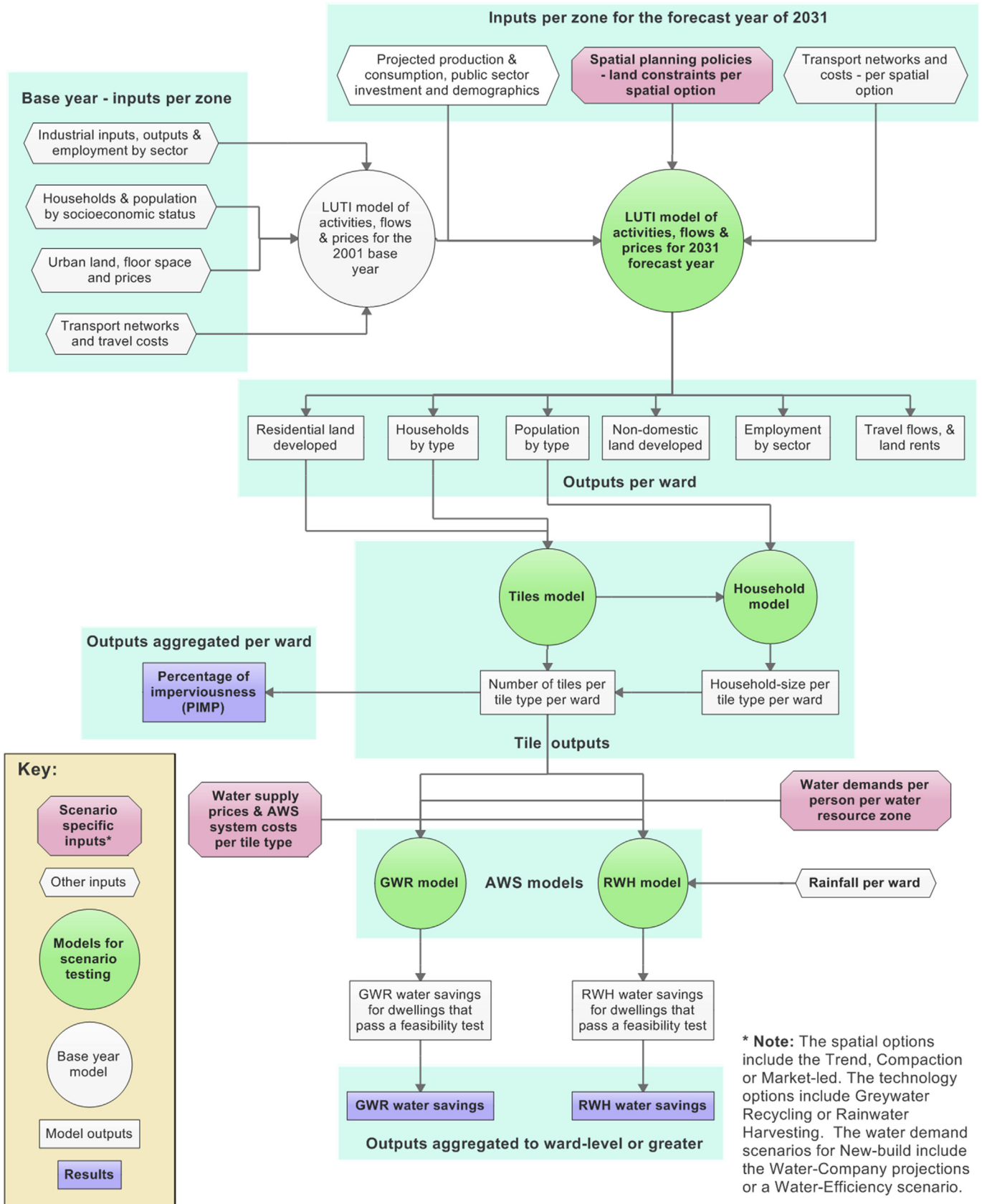**Fig. 2.** Water demand for toilet flushing per WRZ (l/p/d).

Fig. 4. Integrated modelling framework.

Table 1
Spatial scales - listed in order of decreasing scale.

Spatial scale	Data inputs	LUTI modelling (done previously)	Model of households	Model of tiles	Water models	Outputs
Water Resource Zones	✓					✓
Weather stations	✓					
Districts	✓	✓				
Wards	✓	✓	✓	✓		✓
Tiles [a]	✓		✓	✓	✓	✓
Dwellings			✓	✓	✓	

[a] The tiles represent the residential land (approximately 9% of the total study area in the base year).
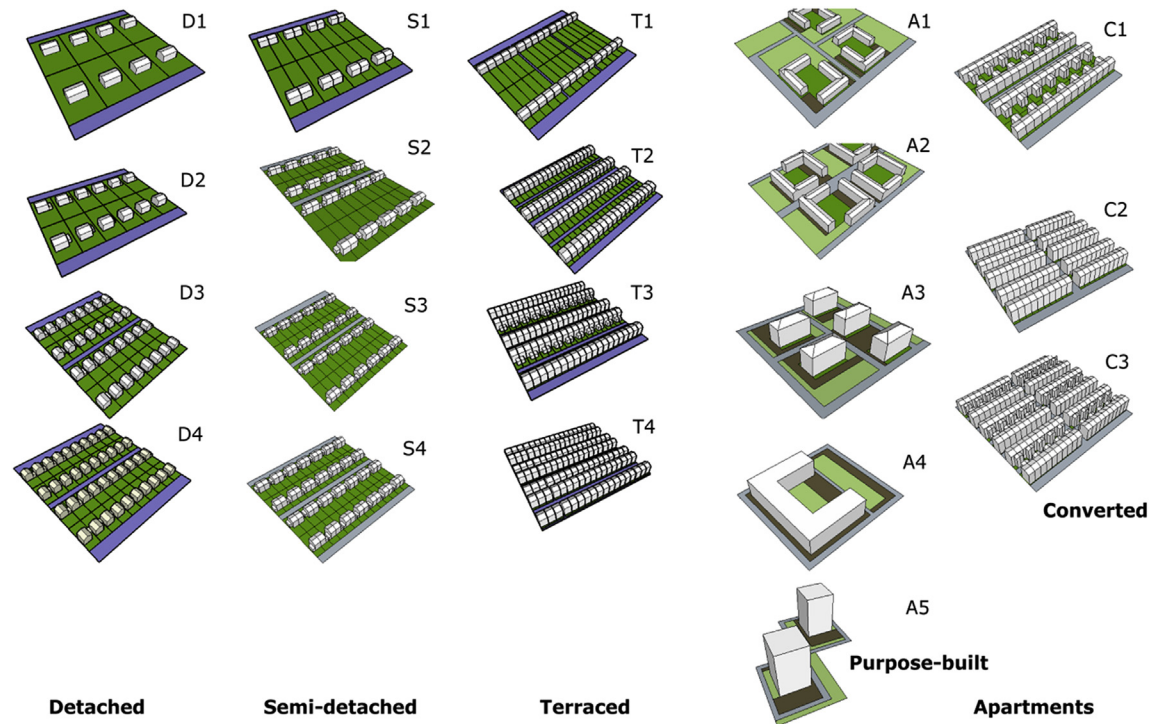

Fig. 5. Schematic illustration of the tiles.

2.3.3. Household model

The inputs to the 'household model' are the tiles and population per ward. The LUTI model takes into account the socio-economic classification of households when forecasting population per unit area of floor space, which thereby indirectly forecasts the household-size per dwelling per ward. The Office for National Statistics and the English Housing Survey provided data on the numbers of occupants per dwelling type per ward. These are then proportionally adjusted per ward using doubly constrained estimation to match the total households and population per ward as forecasts by the LUTI model. Hence, these household-sizes per dwelling type change over the forecast period and vary both spatially and between the spatial planning options.

2.3.4. AWS models of the water-savings

One of the strengths of our novel method is that data specific to each tile are input directly to the AWS models, i.e. its dwelling dimensions, household-size, water demands, land use and rainfall. These models then calculate at building-scale whether AWS would be feasible, and if so, its water savings, thereby completing a calibrated chain of modelling from regional to building-scale. The water savings and system costs are summed per tile and then aggregated per ward, or to whatever spatial scale of output is required.

We have assumed that the supply of greywater for recycling would only be from bathroom washing and bathing facilities and that harvested rainwater would only be from dwelling roof-tops for hygiene reasons. The water saving efficiency of an AWS system depends on its storage capacity and the temporal balance between the supply and demand for non-potable water. Not all of the available inflow will be used because this may either temporally exceed the available storage, or the water demand may exceed supply and the tank runs dry. The amount that is used and results in a water saving is known as the yield.

$$y = E \cdot \mathrm{Min}(C, Q)$$

Where:

y = yield (litres)
E = efficiency of water saving
C = nonpotable demand (litres)
Q = inflow of nonpotable water to the storage tank (litres)

The water saving efficiency for rainwater harvesting is normally calculated using functions that include the dimensionless parameters of the demand fraction d and storage fraction s (Fewkes, 2000);-

$$d = C/Q$$

$$s = S/Q$$

Where:

$S =$ storage tank capacity (m^3)

We have only tested basic AWS systems that had known and calibrated parameters for calculating their water saving efficiency at the time of carrying out the research. These parameters are from published research that simulated systems supplying water for toilet flushing only and they take into account the temporal inconsistencies of water demand and supply. This enabled us to model water-savings and system sizes using the inputs-per-tile of roof areas, rainfall and household water demands. For the GWR systems, we use water saving efficiencies of 0.85 for 'Household' systems (those that serve an individual dwelling) and 0.9 for 'Communal' systems (those that serve multiple apartments) from Liu et al. (2010). However, RWH systems can vary greatly in efficiency because roof area, household-size and rainfall vary between dwellings. We use the modified storage fraction method, devised by Campisano and Modica (2012) that includes annual rainfall and the ratio of dry days to wet days. This enables us to better represent the differing climates from the drier east to the wetter west. Campisano et al. (2013) fitted regression curves to simulation results for sites in climate areas of Italy, classified using the Köppen-Geiger classification scheme (Kottek et al., 2006). We use their regression coefficients for areas in Italy with temperate climate without a dry season, which have similar rainfall to the Greater South East. Our resulting water-saving efficiencies (Appendix A1.5.2) closely match those of the unmodified method in the literature (Fewkes, 2000; Palla et al., 2011).

We assume that these systems would be designed in accordance with the relevant British Standard Code of Practice (BSI, 2009; BSI, 2010), which recommend regular replenishment of stored water to avoid stagnation (daily for GWR and every 18 days for RWH). This has little effect on the water-savings of GWR because the daily supply of greywater and the demands for toilet flushing are relatively consistent. However, it does limit the water saving potential of RWH because it restricts the tank size to 18/365 days of rainfall volume (i.e., to a maximum storage fraction of 0.05). Note that codes of practice and regulations vary internationally and can be conflicting (Yu et al., 2013) and tend to be more supportive in water-scarce countries (Oron et al., 2014).

AWS systems can also supply a wider range of uses than toilet flushing, such as clothes washing and irrigation, but these are more temporally inconsistent. Calibrated parameters for modelling their water saving efficiency and system size were unavailable in the literature and more recent research on this topic, such as Campisano and Lupia (2017) is still local and case-study specific. We would have needed to make dwelling-specific assumptions about appliances and user behaviour to design such systems and this would have been impracticable for our regional-scale modelling. If we had included the supply of water for irrigation this may have affected our findings due to the effects of spatial planning on future garden sizes. However, this is unlikely to have affected our results because these water-savings would be limited by constraints such as storage time, the temporal inconsistency of clothes washing and garden irrigation, and for GWR, the presence of chemicals in the greywater.

2.3.5. Feasibility test of AWS per tile

We have devised a feasibility test to exclude AWS if it would clearly not be cost effective for a dwelling. To make the findings easier to interpret; we assume that all areas would have the same water supply price of £3.5/m³, which is at the top of the current range. AWS is selected for a dwelling if its cost savings on mains water supply would exceed its overall cost within a payback period of 35 years. This is substantially longer than a commercially acceptable rate of return on investment, but may be conceivable for assessing social value. Applying this lenient test to both GWR and RWH ensures that sufficient systems are selected to clearly show how the spatial planning scenarios would affect the future viability of AWS. We estimated the capital, operating and maintenance costs from a review of the literature including; Environment Agency (2011); Friedler and Hadari (2006); Melville-Shreeve et al. (2016). The RWH system costs vary depending on the modelled storage tank capacity. For GWR, a standard system cost has been assumed for Household systems but the cost would be less for Communal systems due to economies of scale, and reduces depending on the number of apartments per block. The feasibility of GWR varies depending on the combination of the water price, system cost and the supply and use of greywater per dwelling (calculated from its household-size and the micro-components of water demand per person). Based on our assumptions, Household-GWR would become noticeably less feasible in areas with less than around 2.2 occupants per dwelling. These factors also affect RWH but its feasibility depends more on rainfall and roof areas. For further details see Appendix A1.6.

2.4. Scenario design inputs

2.4.1. Spatial planning options

We have estimated the inputs for the Trend option from the Local Development Frameworks of the local authorities; the New-build would be on brownfield land with good public transport access. The Trend policy has greater constraints on the release of land than in the past and so the densities of New-build are forecast to be generally higher than Existing dwellings with a greater proportion of terraced houses and apartments. This would be similar to many other city regions that are pursuing 'smart growth' planning policies to constrain sprawl and reduce the need for car travel.

Spatial planning affects where new dwellings are located, and hence their household-sizes and built-form and so we tested two distinct spatial planning options to compare with the Trend option. These comprise of 'Compaction', for which all future urban development would be by infilling at higher densities within existing urban boundaries; and 'Market-led', which would allow development on green-field land in the areas with strongest demand for housing and at lower densities than the Trend. These represent differing views on the priorities for urban development, with Compaction aiming to reduce car travel and energy consumption, whereas Market-led responds to the countervailing socioeconomic pressures for an increase in housing supply where there is greatest demand. The three options are designed by adjusting the inputs to the LUTI model on the amounts of residential land available for development per ward. The LUTI model then endogenously allocates the employment, households and population to the wards, and the resulting residential densities are processed into the tiles and their household-sizes.

2.4.2. LUTI model forecasts

Table 2 summarises the spatial options using a selection of variables and Fig. 6 shows the outputs of the LUTI model for the New-build dwellings and their average densities per ward. London would have the biggest increase in dwellings over the forecast period and, as expected, this would be greatest for Compaction and least for the more dispersed Market-led option. Compaction would result in higher densities than the Trend, whereas Market-led

Table 2
Spatial planning options.

Summary variable	Base year	Spatial option		
		Compaction	Trend	Market-led
Input				
Residential-land	3008 km^2	+6%	+24%	+34%
Outputs				
Average density (New-build)	29dph	+19% (+149%)	+11% (+59%)	+5% (+21%)
Dwellings	8.8million	+38%	+38%	+38%
Apartments	2.4million	+80%	+61%	+44%

would be the least constrained but would still have high densities in areas with the greatest demand for housing. Consequently, Compaction would result in more apartments and terraced houses than the Trend, whereas Market-led would have more detached and semi-detached houses and consume the greatest amount of land (Appendix A1.7 has further details).

2.4.3. Estimating the percentage of imperviousness of residential areas

To illustrate the broader capabilities of our integrated modelling framework, we have estimated the average percentage of imperviousness (PIMP) of residential land (see Appendix A1.8 for details). Compaction would result in urban infilling, often with high rise apartments next to lower density Existing houses, whereas New-build for the other spatial options would be constrained by local planning policies to be more similar to its surroundings. Apartments typically include some green-space, whereas the gardens of high-density houses are mostly paved. Consequently, if comparing wards of the same overall average density in the forecast year, the imperviousness of these areas would be lower for Compaction than the Trend. Our findings closely correspond with the average PIMPs reported in Butler et al. (2018) for existing residential areas of London of 50% for apartments and 55% for dense housing. The advantage of our method is that it can be used to model the impacts of spatial planning policies on the future PIMP of residential land.

2.4.4. Water demand scenarios

Existing dwellings would have water-company estimates of water consumption as a weighted average of metered and unmetered households. There are two scenarios for New-build comprising of either; the 'Water-company' demand projections for metered dwellings; or a 'Water-efficiency' scenario of 120 l/p/d that reflects the water efficiency requirements of UK building regulations. Table 3 shows these water demand scenarios.

The water demand scenarios are input as micro-components of consumption per average person in a WRZ. This simplifying assumption may result in some underestimation of the differences in water consumption between spatial planning options. However, separating the correlated effects of household income, plot-size and water-use in order to understand how spatial planning would affect water demands per dwelling would have required further research.

2.4.5. AWS system scenarios

As shown in Table 4, Household-GWR systems are considered for all dwellings and Household-RWH for houses only. This is based on the optimistic assumption that suitable retrofitting opportunities would arise during the forecast period. Communal-AWS systems are only considered for New-build apartments because the feasibility of networks between houses, or retrofitting Existing apartments, would depend on site-specific factors beyond the scope of our study. We have not tested hybrid systems because

Dixon et al. (1999) found that there was limited advantage in extending a GWR system to also include RWH.

Communal systems may be suitable for some houses, if densely clustered, but their costs, water saving efficiency and applicability would have required research at a more detailed scale. Only a small proportion of New-build houses are likely to be suitably clustered for the Trend but the proportion would be more significant for Compaction. However Communal systems, particularly for GWR, are less acceptable to occupants than Household systems (Domènech and Saurí, 2010; Ward et al., 2013) and this may limit their future uptake for houses. Therefore, only testing Communal systems for apartments is unlikely to have affected our findings.

3. Results

3.1. Impact of spatial factors on the feasibility of AWS

The feasibility of GWR would be positively correlated with household-size and water consumption per person, but this would be less apparent for RWH because roof areas and rainfall are more crucial for its feasibility (Appendix A2.1 provides further details). New-build is directly affected by spatial planning and, in the longer-term, will become an increasingly large proportion of the housing stock, and installing AWS as part of New-build is more practicable than retrofitting. Fig. 7 therefore shows the average water-savings per person per ward for the New-build of the Trend (calculated as the sum of the water-savings for New-build divided by the sum of the occupants of all New-build dwellings). The scatter plots illustrate how these water-savings vary between wards of similar density (the lines show the average value, rather than purporting to be a trend). The maps illustrate how water-savings would differ greatly between adjacent wards, indicating that targeting the most appropriate technology to a locality would require spatial detailed modelling. The feasibility of Household-GWR would be finely balanced between its water-savings and its cost per household and so the water-savings of GWR (Fig. 7a) would be low for many wards but for a few it would meet almost all of the water demand for toilet flushing (described in Section 2.2.2). This shows the importance of modelling future household sizes and water demands. Household-GWR would rarely be cost effective in wards with small households and, or low water demands (as can be seen by comparing its water-savings with Figs. 1b and 2). However, the water-savings of RWH (Fig. 7b) vary less between wards of similar density because they are more closely related to rainwater supply. They would therefore be low in higher density areas because these have less roof area per dwelling (Appendix A1.1) and also in dryer areas (e.g. east of London).

3.2. Comparison of the AWS water-savings between the spatial options

Fig. 8 shows the dwellings and water-savings aggregated to the
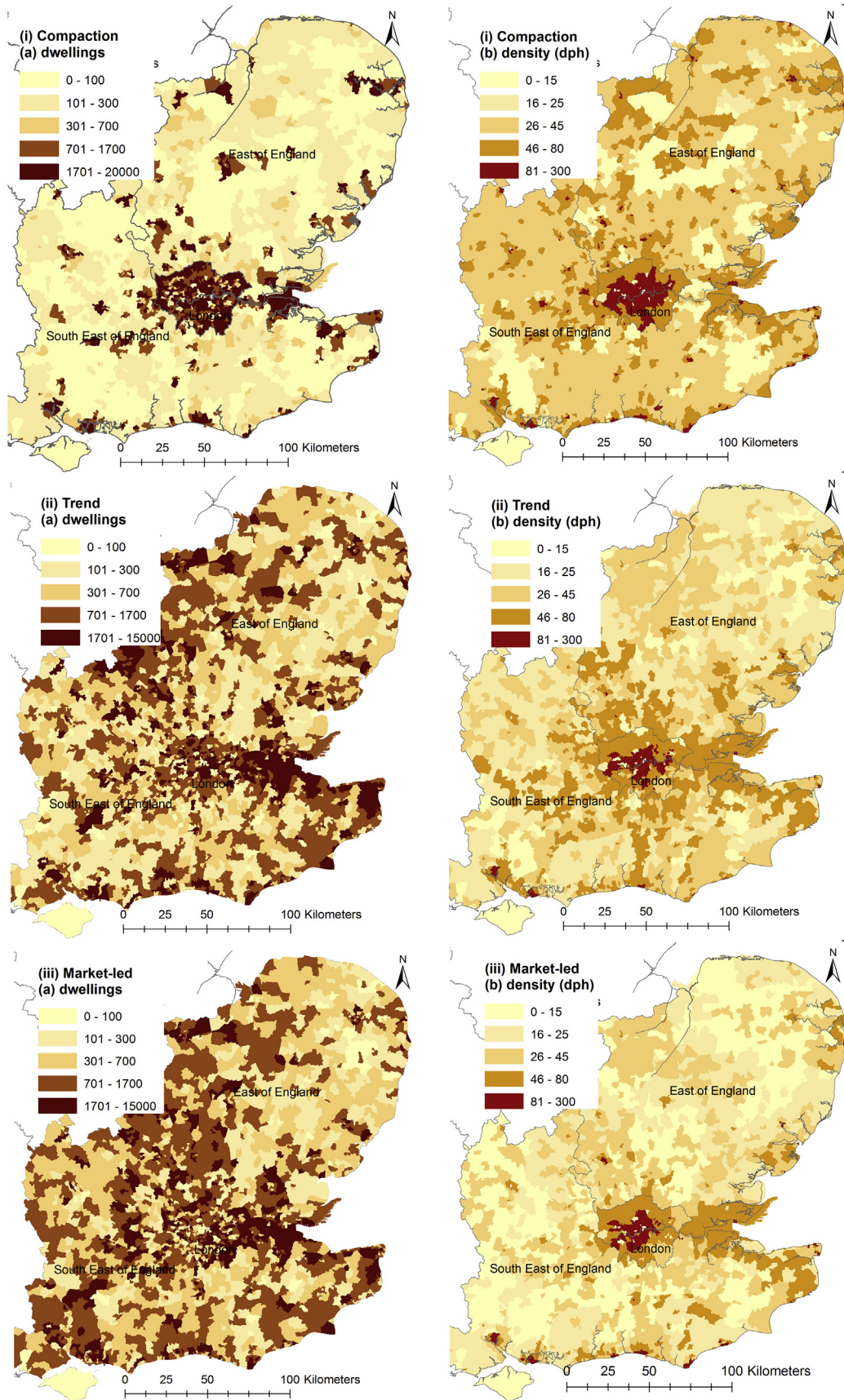
Fig. 6. Comparison between the three spatial planning options on the number of New-build dwellings (a); and their average densities (b), per ward.

Table 3
Water demand scenarios ('Water-company' or 'Water-efficiency').

Year	Development	Water demand scenario
Base year	Existing	Water-company data for metered and unmetered
2031	Existing	Water-company projections for metered and unmetered
	New-build	'Water-company' projections for metered
		'Water-efficiency' (120 l/pd)

Table 4
Water technology scenarios ('GWR' or 'RWH').

Year	Development	Building-type	AWS	System type
Base year	Existing	All dwellings	None	n/a
2031	Existing	Houses	GWR or RWH	Household
		Apartments	GWR	
	New-build	Houses	GWR or RWH	
		Apartments	GWR	Communal or Household [a]
			RWH	Communal only

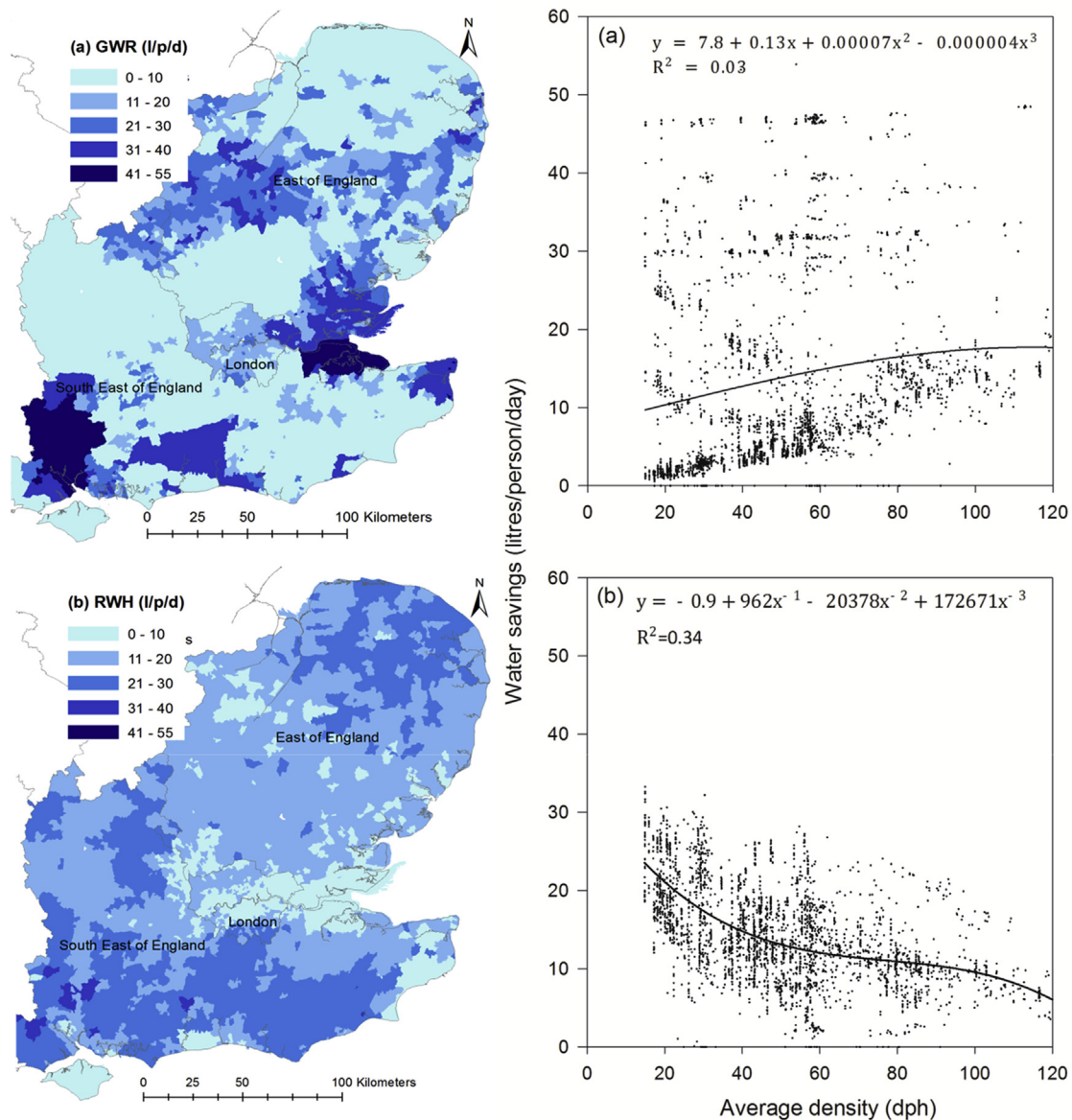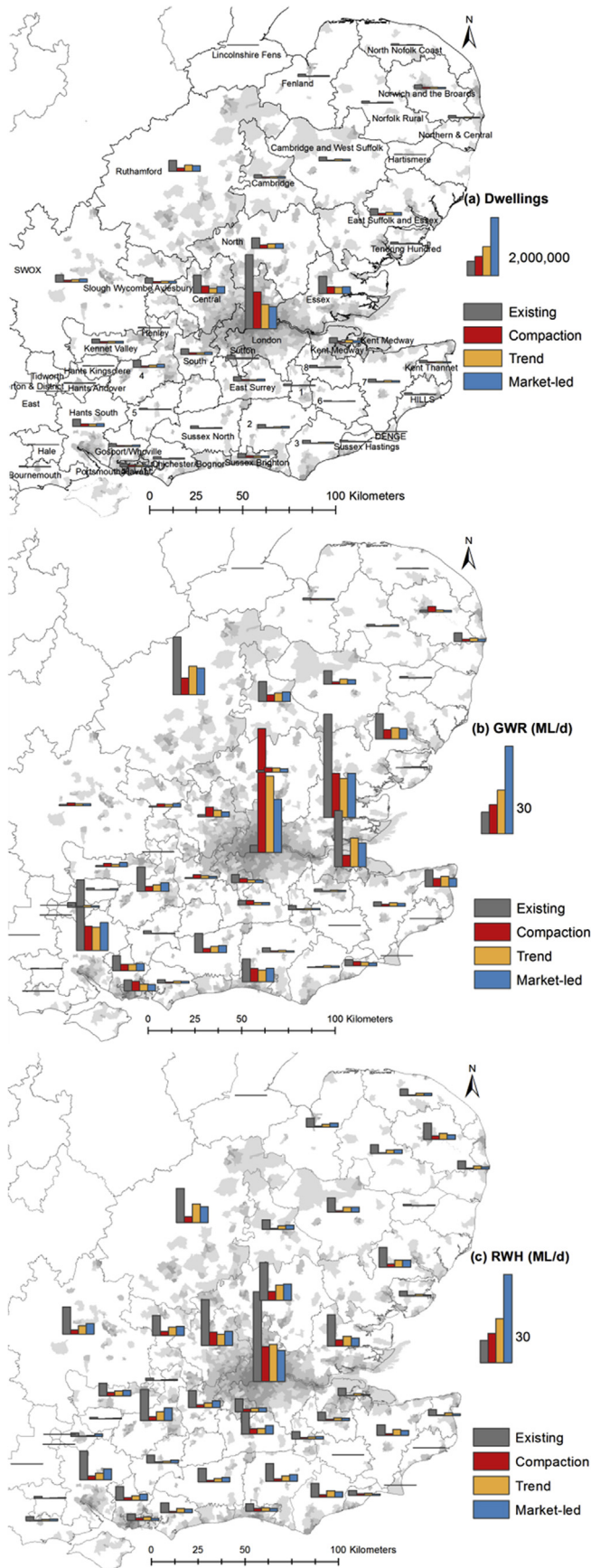[a] Communal was almost always selected as being the most cost effective.

Fig. 7. Average density versus water-savings per ward of GWR (a); and RWH (b) for New-build.

Fig. 8. Comparison per WRZ of dwellings (a); and water savings of GWR (b) and RWH (c) for 'Existing' and 'New-build per spatial option' (the 2,000,000 in the legend of map (a) represents the attribute value of a bar on that map of the same size as the right-hand bar of the legend).

WRZ scale for Existing dwellings and the New-build of each spatial option (Appendix A2.2.1 explains the aggregation process). There would be clear differences in water-savings between Existing and New-build, especially for rapidly growing urban areas, such as London. GWR would be more viable for New-build than Existing because our scenarios included Communal systems for New-build apartments. Conversely, RWH would be slightly less viable for New-build than Existing because New-build would generally be of higher density.

Spatial planning would obviously affect not only the built-form of New-build, but also how the future water demands would be distributed spatially within the study area. The water savings therefore differ spatially between the spatial options depending on both the amount of development and how spatial factors affect its suitability for AWS. Compaction with GWR (Fig. 8b) would have the greatest water-savings for the urban centres, such as London, partly because it would have the greatest increase in dwellings in these areas (Fig. 8a) and partly because they would be at higher densities with a greater proportion of apartments. Conversely, RWH (Fig. 8c) is best suited to lower density areas and so its water savings would be greater for the more dispersed, lower density development of the Market-led option. These findings show the importance of taking into account spatial planning, if formulating long-term policy support for AWS.

3.3. The relationships between residential density and potential water-savings

The following charts show the average water-savings per person within 10 dph wide average density bands to smooth out some of the variability (i.e., the total water-savings divided by the total occupants for all wards within the average density band, for either Existing or New-build). At higher densities, these water-savings per person are greater for New-build than Existing due to the Communal systems, and this is particularly noticeable for GWR (Fig. 9a). The water-savings of RWH (Fig. 9b) generally decline with increasing density due to less roof area per person. The water-savings of AWS would be much lower for the 'Water-efficiency' scenario because, although Communal systems would still be feasible, Household systems would rarely be cost effective with such low water demands. Although the results for Household and Communal systems are not shown separately; those for New-build Household systems are similar to those for Existing (Household) systems.

We have tested New-build with either £0.50 higher or £0.50 lower water prices. Fig. 9c shows that the water-savings for GWR are very sensitive to water price, especially in low and medium density areas because if the water price were lower, then fewer Household-GWR systems would pass our feasibility test and vice versa (Communal-GWR is less sensitive to water price because its cost per dwelling would be lower). This suggests that the future feasibility of GWR would increase if Household systems could be better tailored to suit different household sizes and characteristics. RWH would be more robust to uncertainties about future water prices (Fig. 9d). However, its water savings would be sensitive to rainfall because this has a greater affect on its cost effectiveness; particularly in higher density areas where dwellings have less roof area per occupant (see Appendix A2.2.2). Further research could more fully explore the impacts of climate change by using rainfall projections.
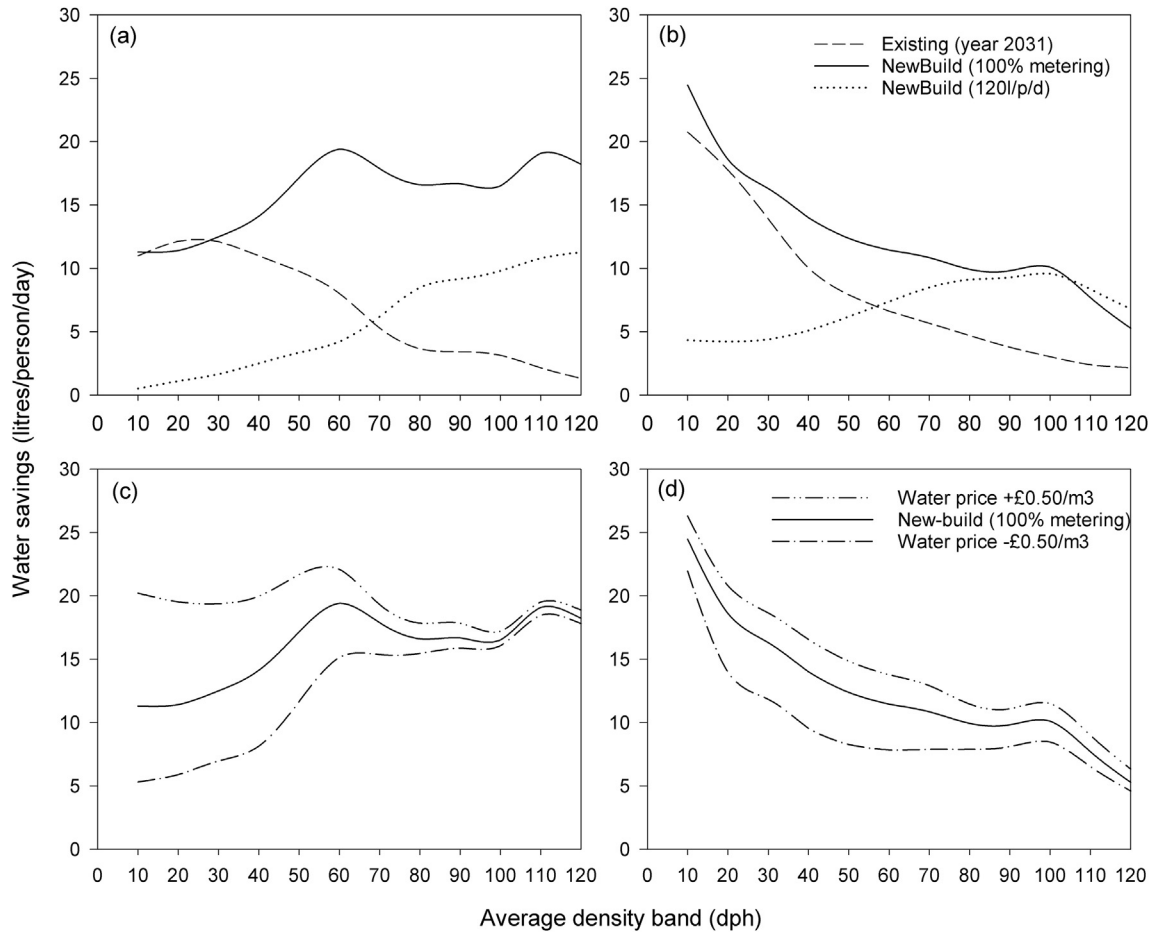
Fig. 9. Average density versus water-savings of GWR (a); RWH (b); and the sensitivity to water price of New-build water-savings of GWR (c); and RWH (d).

3.4. Comparison with methods that use standard dwelling typologies and household-sizes

Previous models (Thi Hoang Duong et al., 2011; Kim and Furumai, 2012; Thames Water, 2017) used an average household-size per dwelling type and, or standard dwelling typologies. We therefore compare our findings with those that we would have obtained by using these more aggregate methods.

Fig. 10a compares the GWR water-savings for New-build using average household-size per dwelling type with our results shown
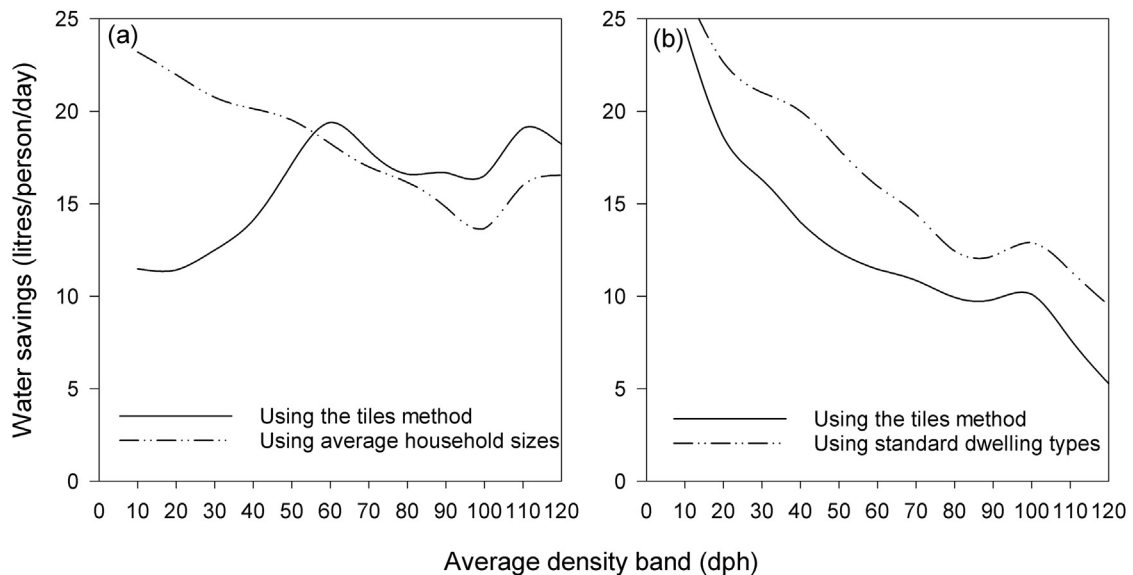

Fig. 10. Average density versus water-savings – comparison of the tiles method with (a) GWR using average household-sizes; (b) RWH using standard dwelling typologies.

in Fig. 9a (i.e., using household-sizes of 2.5, 2.4, 2.3 and 1.7 for detached, semidetached, terraced and apartments respectively from UK census data). Using these average household-sizes would have substantially overestimated the water-savings of GWR for wards with average density less than around 55 dph (i.e., most of the wards). The reason is that Household-GWR systems are less feasible for smaller households and many wards have smaller than average households (see Fig. 1b). Therefore, a method that assumes average household-sizes would overestimate how many dwellings would be feasible for GWR and hence the total water-savings per ward.

Similarly, Fig. 10b compares the water-savings per person of RWH using the standard typology per dwelling type with our results in Fig. 9b for New-build. This shows that using average dimensions per dwelling type would consistently overestimate the water-savings by around 25%. The reasons are that some dwellings are smaller than average for their type and so are less likely to have sufficient roof area for RWH to be cost-effective. Also, as mentioned in Section 2.3.2, the frequency distributions of plot density per dwelling type are positively skewed, signifying that the majority of dwellings have smaller dimensions than if calculated as an average. Consequently, if we had used standard dwelling typologies, we would have overestimated the feasibility of RWH and hence the water-savings.

4. Discussion

Future urbanisation is likely to be higher density than before and consequently the water saving potential of AWS will differ between Existing dwellings and New-build. Estimates based on projections of the housing stock would therefore be unsound. Instead, our novel integrated modelling framework embeds detailed water modelling within a practical model for long-term urban planning that provides inputs to the AWS modelling at the building-scale. This is an advance in water modelling and the urban modelling and water modelling are inseparable for this purpose.

Our findings on the relationships between individual factors match what would be expected from the literature. However, it would have been very difficult to understand their future combined effect, and how this would vary spatially, without the aid of this integrated modelling framework. The results are conditional on our choice of inputs and assumptions but these can easily be adjusted.

This type of modelling tool could be useful for constructive engagement between water companies and planning authorities on scenario analysis for urban development and water resources planning. It has the potential to test scenarios for various aspects of water management related to spatial development, built-form and water demands.

The methods could be applied internationally if the models are recalibrated to local data and standards. The outputs of tiles and households could also be used as a spatial database for more spatially detailed modelling of future urban layouts and urban water management.

5. Conclusions

- Our integrated modelling framework represents how spatial planning would affect the future location of dwellings and their variability in roof areas and household-sizes so that the impacts of spatial planning on the future feasibility and water-savings of AWS can be modelled at the building-scale, which is an important advance on previous methods.
- Methods based on standard typologies and household-sizes would substantially overestimate the future water-savings by

failing to identify how many dwellings would have insufficient roof area or household-size for AWS to be cost effective.
- Spatial planning would greatly affect the feasibility and water-savings of RWH because it affects the location and urban densities of New-build and hence rainfall, roof areas and rainwater per person. Household-GWR would be less affected by spatial planning but its feasibility would be more finely balanced between the system cost and its water-savings, showing the importance of our modelling of spatial differences in future household sizes. Communal systems would depend on the suitability of future built-form and hence spatial planning.
- The Market-led option would generally result in lower density development and thereby increase the water saving potential of RWH; conversely Compaction would lead to a greater concentration of higher density development and would increase the water saving potential of Communal systems, particularly GWR.
- The findings suggest that forecasts of residential densities, rainfall and water price could be used in conjunction with more detailed local studies to indicate how spatial planning would affect the future water saving potential of AWS. This may help to identify the most suitable type of AWS for a locality and enable coordination between planning authorities and water companies on targeted bottom-up policy support, such as building design standards, subsidies and local planning guidance.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.watres.2019.06.029.

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