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Distributed Water Infrastructure for Sustainable Communities

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Abstract Distributed water infrastructure (located at the community or the household level) is relatively untried and unproven, compared with technologies for managing urban water at higher (e.g. regional) levels. This work presents a review of currently available options for distributed water infrastructure and illustrates the potential impact of their deployment through a number of indicative infrastructure strategies. The paper summarises the main categories of both centralised and decentralised water infrastructure, covering all three flows (water supply, wastewater and drainage) and their integration through recycling and reuse. The potential impact of the identified infrastructure options for urban water management is examined. The desirability of the strategies examined, is dependent on (case specific) constraints to urban development, including for example regional or local water resource availability, treatment plant capacity, cost of upgrading infrastructure, potential for (distributed) energy (micro) generation and climatic changes (and other non-stationary processes). The results are presented and discussed. It is concluded that there is currently a significant potential for a range of improvements in urban water management which could result from the context-aware deployment of a portfolio of technological infrastructure options. It is also suggested that there are trade-offs between water use, energy use and land use, and these have an equilibrium point that is associated with the technological state-of-art. At a given technological state-of-art, further reductions in water savings signify increase either energy consumption (for high-tech solutions) or land use (for low-tech solutions). The strategies' evaluation indicates however, that until this equilibrium point is reached there can be significant gains in all three aspects. After this equilibrium, improvements in one aspect

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inevitably signify costs in others. The choice of desired trade-off then depends on the specific constraints of the problem at hand.

Keywords Decentralised • Distributed water infrastructure • Micro-generation • Strategies • Urban water

1 Introduction

The discussion on centralised versus distributed water infrastructure has been going on for some time within the urban water community, starting with drainage systems (end-of-pipe versus source control or Sustainable Drainage Systems (SUDS): Woods et al. 2007; Rauch et al. 2005; Makropoulos et al. 1999) and moving on to local wastewater treatment, rainwater harvesting and lately recycling (Memon et al. 2007; Makropoulos et al. 2008a, b; Frazer-Williams et al. 2008).

It could be argued that this is part of a larger trend towards devolution of resources management and (ultimately) more local stewardship of the environment which can be discerned in such diverse areas as:

- energy generation (microgeneration: Alanne and Saari 2006; Cherni et al. 2007 which is also linked to water: Jaramillo et al. 2004; Ashok 2007; Vieira and Ramos 2008; Koutsoyiannis et al. 2009),
- catchment level management plans (vis a vis the WFD) and
- community-level environmental decision making and governance (Tidwell et al. 2004; Marks and Zadoroznyj 2005; Evan et al. 2006; Brown and Farrelly 2009).

The link that is made implicitly or explicitly is one between local management and empowered, engaged and ultimately sustainable communities (Pahl-Wostl and Hare 2004; Folke et al. 2005), a conceptual link which is also sometimes subject to debate (Wilder and Lankao 2006).

Within this context, urban water systems have often been discussed at two levels: the small, household scale (e.g. Surendran and Wheatley 1998; Cowden et al. 2008) and the large, city-wide scale (e.g. Mitchell et al. 2001; Mitchell and Diaper 2006). Less attention has been devoted to the intermediate level: that of the small new development, community or neighbourhood (van Roon 2007; Makropoulos et al. 2008a, b).

In this paper we focus on the household and intermediate scales and investigate the impact of the choice of urban water management technologies on a number of indicators, including water and energy consumption.

The paper initially presents currently available options for water management at a variety of scales. The difficulties in categorisation inherent in such a work are presented and discussed to some extent. After identifying the options, the paper sets out some of the most promising systems for a more detailed discussion. Alternative strategies, representing bundles of compatible technologies have been identified to help focusing on a number of promising technologies in the short, medium and longer term. Four such strategies (some realistic and others more radical) are presented and appropriate indicators for their assessment introduced. Finally, a hypothetical case study is defined, allowing for a context-aware discussion of the effect of each strategy on urban water management and its main conclusions presented and discussed. The paper concludes with an identification of knowledge gaps and promising new avenues for research, to assist strategic research prioritisation and planning.

2 Technological Options

The main urban water management infrastructure options and technologies were identified and grouped, into the three water flows (water supply, wastewater and drainage) and their integration (through recycling/reuse) for both centralised and decentralised applications (Table 1). This collection, review and categorisation was undertaken to map the set of potential options available to developers and is included here as a resource for the benefit of "optioneering" type of analysis at the early stages of a new development or retrofit intervention. It also provides the possibility space from which the strategies presented here were able to draw.

Clearly, technologies may conceptually belong to more than one category and the distinction between centralised and decentralised applications is a difficult one to make. Sometimes, it may even be irrelevant (are water containers a centralised or a decentralised water supply technique?).

In this paper, we defined centralised techniques and options as those referring to applications that favour city-wide scales, including wide-area distribution networks, large storage water facilities and the development of large-scale resources. Decentralised options are defined as those being applicable at the development level (for example, up to 5,000 households). They include in-house options, if these could be applied extensively enough to have an impact on infrastructure (for example, water saving devices are part of this category). Another distinction made in this work, defines a technology as "conventional", "novel but used somewhere" or "novel". The assumption here is that conventional options are those that could appear in a 'business as usual' scenario in Europe and particularly in the UK (Butler and Makropoulos 2006). So, for example, separate sewers, which have been a mainstream infrastructure option for wastewater management all over Europe, fall under the conventional category. Novel but used somewhere technologies are those that are not currently widespread in Europe (such as for example urine separation, small diameter sewers etc), but have found successful application, beyond the prototype scale, somewhere—in Europe or the rest of the world (e.g. Berndtsson 2006; Otterpohl et al. 2003). The final category is 'novel', which refers to processes that are essentially experimental or still undergoing development, such as air-displacement toilets.

It should be noted that the distinction between the three flows and the recycling category is also a difficult one to make, since recycling is clearly an integration of a number of flows. Dual water supply, for example, can fall under water supply and recycling. In this paper, we have included dual water supply under recycling technologies that allow an almost closed loop between water demand and wastewater generation. For example, in the case of dual supply under the water supply flow, we describe the technology without considering the source of the non-potable fraction. In recycling, we take the specific case of a non-potable fraction, that of treated grey water.

Bearing the above categorisation difficulties in mind, some of the most important urban water infrastructure-related technological options were included in the tables

Table 1 Summary of technology characteristics within the various flows

	Description
Water supply	
Water supply reservoirs	Large-scale rainwater storage in upland locations of generally good quality water.
Groundwater abstraction	Large-scale exploitation of aquifer water of generally good quality water.
Surface water abstraction (indirect wastewater reuse)	Large-scale use of (typically) river water of variable quality. Water abstracted may include treated sewage effluent from upstream urban areas.
Transfer of resources	Large-scale engineered transfer of water resources from locations with abundant supply.
Desalination	Treatment of seawater or brackish water to potable (drinkable) standard. High energy costs and residual brine.
Dual supply systems	Two pipe systems, one conveying potable water and one non-potable. Danger of cross-connections.
Direct wastewater reuse	Treatment of sewage to potable water standards is technically possible but is extremely rare even in the most water-stressed areas.
Water containers	The consumption of water delivered by bottle is growing at a rapid rate. Potable water delivery using bottled water is very user acceptable.
Water saving devices	In-house new or retrofit devices that use less water for similar function.
Local abstraction	Similar to groundwater abstraction except practised on a local scale and typically for non-potable applications.
Fit-for-purpose supply	Careful assessment of the water quality standard needs for a particular use, matched to type of water available on the site.
Point of use treatment systems	A variety of in-house equipment (such as filters, UV disinfection, softening) for water treatment.
Stormwater	
Combined sewers	System of sewers conveying stormwater (surface water runoff) and wastewater in the same pipe. Potential pollution from CSOs.
Separate storm sewers	Two pipe system conveying runoff and sewage in separate pipes. Danger of misconnections.
Underground storage systems	Below ground storage of stormwater in tanks or oversized pipes, for controlled release after the storm event.
Combined sewer overflows (CSOs)	Overflow devices on combined sewers that operate under high flows (rainfall induced), discharging untreated but dilute sewage to watercourses.
Surface detention systems	Above ground storage of stormwater in ponds and lakes, for controlled release after the storm event.
Gully pots/inserts	Sump under-road gully inlets to trap sediment. Inserts designed to improve trapping performance.
Wetlands	Naturally-occurring vegetated waterbodies that may improve stormwater quality.
Sand filters	Engineered filters with sand media for stormwater quality improvement.
Inlet control	Small-scale devices (disconnected downpipes, rainwater butts, surface ponding) designed to delay stormwater runoff.

Table 1 (continued)

	Description
Swales and filter strips	Flat strips or gently side-sloped grassed ditches for stormwater conveyance and treatment.
Pervious surfaces	Engineered hard surfaces allowing infiltration of stormwater into the sub-surface.
Soakaways	Underground chamber filled with crushed stone allowing infiltration of stormwater into the surrounding sub-soil.
Infiltration measures	Other forms of stormwater infiltration device such as trenches and blankets.
Filter drains	A type of filtration trench including a buried perforated pipe for drainage; popular for rural road drainage.
Ponds	A type of above-ground stormwater storage area, which may be natural or engineered, for flow attenuation and quality improvement.
Constructed wetlands	Engineered version of natural wetlands. Large areas required, but have water quality improvement properties and aesthetic and biodiversity benefits.
Vegetated spaces	Areas of land set aside for stormwater collection and treatment, with similar benefits to constructed wetlands.
Bioretention basins	Shallow basins used to slow and treat on-site stormwater using native soils.
Sediment basins	Basin constructed to trap sediment by settling under gravity.
Modular systems	Various ‘off the shelf’ treatment units, such as sediment basins and constructed wetlands for stormwater treatment.
Built-in storage	Proprietary devices built into the housing structure to detain stormwater, typically underground.
Evaporative SUDS	Devices designed to maximise evaporation of stormwater and minimise site runoff.
Wastewater	
Combined sewer systems	System of sewers conveying stormwater (surface water runoff) and wastewater in the same pipe. Potential pollution from CSOs.
Separate foul sewer	Two pipe system conveying runoff and sewage in separate pipes. Danger of misconnections.
End-of-pipe wastewater treatment plant	Treatment of wastewater from centralised sewer system using physical, chemical and biological processes prior to discharge to the environment.
Real time control	Active control of sewers or treatment plants based on real-time conditions, aimed at optimising performance.
In-sewer treatment	Measures to promote and facilitate biological degradation of wastewater within the sewer system itself.
Cesspools	Small-scale solution consisting of a closed tank for storing wastewater, requiring regular emptying.
Septic tank systems	Small-scale solution consisting of a tank for storing wastewater, followed by a drainage field for dispersing flow to the sub-soil. Requires less frequent emptying.
Package treatment plants	A range of proprietary devices built at small scale but mimicking the processes found in end-of-pipe plants.
Mound systems	Specialised drainage system used when sub-soil properties are not ideal for septic tank installation.

Table 1 (continued)

	Description
Constructed wetlands	Same as detailed in stormwater table, but used for treating wastewater prior to discharge to watercourses.
Sand filters	Same as detailed in stormwater table, but used for treating wastewater prior to discharge to watercourses.
Membrane bioreactors	Treatment process, based on biological degradation in conjunction with ultra-filtration, producing an extremely high quality treated effluent.
Living machines	Series of biological treatment processes based on emergent vegetation and constructed within a greenhouse environment. Possible amenity benefits.
Small diameter gravity systems	Small-sized foul sewers used to convey low flows or standard flows with initial removal of solids (for example, via a septic tank).
Low pressure sewers	Pumped outlet from toilet or septic tank conveyed under low pressure.
Vacuum toilets/sewers	Vacuum pressure used as motive force to drain toilets directly or via wastewater sumps.
Air-displacement toilets	Very low flush toilets using displaced air as the main motive force.
Recycling/reuse	
Aquifer storage and recovery	Recharge of underground aquifers with stormwater or treated wastewater, either through pumping or gravity feed, for later use.
Effluent dual reticulation	Similar to dual water supply except treated wastewater is used for the secondary supply
Rainwater harvesting	Collection and storage of rainfall from roofs and reuse for non-potable applications.
Grey water systems	Collection and storage of household washwater for treatment and reuse for non-potable applications.
Green roofs	Vegetated building roofs used to capture, store, release and evaporate rainfall.
Combined rainwater and greywater recycling	Systems incorporating elements of both rainwater harvesting and greywater recycling.
Dry toilets	Toilets requiring no or minimal water use, such as pit latrines, chemical toilets, incinerating toilets.
Composting toilets	Toilets that collect faeces and urine and exploit the natural composting process to produce a natural fertiliser.
Urine separation	Specially-designed toilets that allow urine to be collected separately from faeces for use as a natural liquid fertiliser.
Sewer mining	Pumped wastewater from local sewers for reuse applications after treatment.
Autonomous housing	Houses that are (almost) completely self-sufficient, including in their use of water.
Closed water systems	A system where all domestic wastewater is collected and treated for potable use. No known systems available for practical everyday use.
Energy–water systems	A range of technologies or practices that harness energy from the various water flows and in so doing achieve energy efficiency and/or treatment measures.

Table 2 Centralised and decentralised technologies

	Centralised	Decentralised
Water supply	Water supply reservoirs Groundwater abstraction Surface water abstraction (indirect wastewater reuse) Transfer of resources Desalination Dual supply systems Direct wastewater reuse Water containers	Water saving devices Local abstraction Fit-for-purpose supply Point of use treatment systems
Stormwater	Combined sewers Separate storm sewers Underground storage systems Combined sewer overflows Surface detention systems Gully pots/inserts Wetlands Sand filters	Inlet control (downpipes, butts, ponding) Swales and filter strips Pervious surfaces Soakaways Infiltration measures Filter drains Ponds Constructed wetlands Vegetated spaces Bioretention basins Sediment basins Modular Systems Built-in storage Evaporative SUDS
Wastewater	Combined sewer systems Separate sewer systems End-of-pipe wastewater treatment plant Real time control In-sewer treatment	Cesspools Septic tank systems Package treatment plants Mound systems Constructed wetlands Sand filters Membrane bioreactors Living machines Small diameter gravity systems Low pressure sewers Vacuum toilets/sewers Air-displacement toilets
Integration: recycling/reuse	Aquifer storage and recovery Effluent dual reticulation	Rainwater harvesting Grey water systems Green roofs Combined rainwater and grey water recycling Dry toilets Composting toilets Urine separation Sewer mining Autonomous housing Closed water systems Energy-water systems

Conventional   Novel but used somewhere   Novel below. Table 1 provides a list and a short description of options (from conventional to novel) for each urban water flow, including their integration through recycling. Table 2 makes the distinction between centralised and decentralised level of application for these technologies, in the specific sense these two terms are used in this work. A more detailed description of these technological options can be found in Butler and Makropoulos (2006). A common colour key is included after Table 2 differentiating the technologies in terms of the conventional or otherwise of their application.

3 Alternative Strategies for Infrastructure Systems

This section identifies a series of compatible infrastructure options (hereafter termed "alternative strategies") including options for water, wastewater, drainage and recycling, for delivering water services in new urban developments. It then discusses their potential impact on a number of sustainability indicators.

Interest in and work on selecting sustainable options, including the development of scenarios for urban water management is a relatively recent development and the subject of current research (for example, Makropoulos et al. 2008a, b). In this work we have defined a number of alternative strategies, (both realistic and more radical). The realistic strategies represent an obvious 'next step' to existing conditions and regulations. The more radical strategies included in this analysis are more context dependent and aim to present solutions to more extreme constraints, including, for example, severe limitations in the wastewater system capacity or severe limitations in the water supply system capacity. They are not presented here as suggestions of a stepwise change in policy towards these more radical solutions, but rather as boundaries of available options that illustrate what is technically feasible under the severe limitations that could be encountered in the future.

A short description of the alternative strategies is included below:

3.1 Strategy 1: Benchmark

The Benchmark assumes current practice, with all services (water supply, stormwater and wastewater) sufficiently centralised and no recycling or reuse. In terms of infrastructure, the benchmark is guided, as an example, by the 2002 UK Building Regulations, which specify metering for all new properties, use of 6-L toilets and implementation of (some) SUDS (Sustainable Urban Drainage Systems) for stormwater control in the form of, for example, down pipe disconnection and pervious surfaces. It must be noted, however, that most of the existing housing stock in the UK (and indeed in most of the world) has been developed with water and energy saving standards that are lower than the 2002 UK Building Regulations prescribe. As such, expected improvements following the implementation of the technology identified in the strategies should be more pronounced relative to the existing housing stock than they are relative to the benchmark.

3.2 Strategy 2: Next Step

The Next Step strategy represents a balanced short-to-medium term portfolio of technological options, representing a logical continuation of water policy development. In this case, the benchmark is amended by including further household water efficiency measures and 'smart' metering. A distinction is made between potable/non-potable water. The strategy incorporates a dual water supply system, with non-potable water sources (local groundwater or rainwater) exploited at *community level*. There is no change to the wastewater management technology. Stormwater management is amended by including more extensive source control measures and/or on-site underground storage. Other technologies are employed to improve stormwater quality, such as ponds, constructed wetlands or infiltration basins, subject to space availability.

3.3 Strategy 3: Limited Central Infrastructure

This more radical strategy should be viewed as a set of technological options that are available as a response to harder context-dependent constraints, resulting from infrastructure or climatic limitations. What is of primary concern here is to minimise both the water required from central supply and the amount of wastewater discharged into the central wastewater system. In this strategy, the non-potable component of the dual supply (introduced in Strategy 2) is provided by recycled greywater at community level, which, although more difficult to treat than rainwater, should be considered a more reliable/stable supply. Stormwater is collected as part of the stormwater management strategy and its quality improved via Sustainable Drainage Systems (SUDS) before being discharged to local watercourses. Very low flush toilets are employed both to minimise the amount of greywater required and to minimise wastewater export. Small-bore sewers are employed for wastewater collection. The central wastewater treatment plant (WWTP) receives less but stronger wastewater. Resource recovery (energy, heat and nutrients) is more readily and widely practiced at the WWTP level, assisted by the availability of stronger wastewater inflow.

3.4 Strategy 4: No Central Infrastructure

This is the most radical strategy that was developed. It illustrates available technological options for managing situations where external constraints include very limited or non-existent central water and wastewater infrastructure, due to, for example, significant distance to existing works, high costs of upgrading or resource unavailability (for instance, due to climatic conditions). Both local rainwater and local groundwater is collected in this case for both non-potable and potable use. Water is treated at point of use for potable applications. Bottled water is used to back up the potable supply when necessary. The rainwater harvesting system is also used for stormwater management through the existence of sufficient storage. Communal cesspools are linked to houses with small bore sewer systems. The wastewater is then treated by applying it to willow plantations at a local/regional level. The resulting biofuel is used at local CHP (Combined Heat and Power) plants.

Summaries of the technologies used, for each strategy, are detailed in Table 3.

3.5 The 'Sustainable Community' Case Study: NewPlace

A specific urban development setting is required to assist the comparison between the alternative strategies. This is provided by a hypothetical case study (referred to

Table 3 Technologies used in each strategy

Strategy	Water supply	Stormwater	Wastewater	Recycling/reuse
1. Benchmark	Centralised potable water provision Metering	Disconnected downpipes Pervious surfaces Separate storm sewers	6-L toilets Foul sewers End-of-pipe treatment	None
2. Next step	As 1 plus: Water saving devices 'Smart' metering Dual supply (potable and non-potable) Community based non-potable water source from ground water or rainwater	As 1 plus: Additional source control measures Onsite storage Ponds/small wetlands/ infiltration measures Separate storm sewers	As 1	Rainwater or groundwater
3. Limited central infrastructure	As 2 except: Non-potable supply from greywater	As 2	Very low flush (1.5 L) toilets Small bore systems End-of-pipe treatment	Greywater
4. No central infrastructure	As 2 except: No centralised provision Point-of-use treatment for both potable and non-potable supply	As 2 plus: additional onsite storage	Very low flush (1.5 L) toilets Communal cesspools linked to houses with small bore systems Biofuel production (willows)	As 2

hereafter as 'NewPlace'), representing, as an example, a plausible new development under the assumptions and forecasts for new urban developments in the South East of England (where housing densities need to be relatively high and size of new developments is significant (see Table 4). The South East of England (where London is also situated) presents a challenging situation where new developments need to be located within areas where existing infrastructure is close to or at capacity (making this a context of world wide relevance).

The hypothetical development of NewPlace is specified as follows:

- *Development type*: urban extension
- *Size*: 75 ha
- *Housing density*: 50 dwellings per hectare
- *Occupancy*: 2.4
- *Total population*: 9,000
- *Land use*: 35% open space, 20% paved area and 45% roofed area.

Table 4 New place water use parameters

Parameter (units)	Value
Potable water used (L/capita/day)	145.6
Microcomponents used to calculate water demand:	
WC = 24.6 L/capita/day	
Bath = 24 L/capita/day	
Shower = 27 L/capita/day	
Washing Machine = 12 L/capita/day, taps/sinks = 27 L/capita/day, dishwasher = 16 L/capita/day and outdoor and other miscellaneous uses = 15 L/capita/day	
Non potable water used (L/capita/day)	0
Total wastewater generated (L/capita/day)	136.8
Stormwater generated (L/capita/day)	89
Energy use (kWh/capita/day)	0.18
Rainfall (mm/year)	600

Wastewater is managed using 6-L toilets, with an end-of-pipe treatment plant whose energy use is 820 kWh/ML (Balkema 2003). The values in Table 4 are similar to those quoted in a number of relevant reports (including Styles 2005). They are also consistent with the generally accepted water consumption figure of 150 L/capita/day for the case study area (the South East of England).

3.6 Performance Indicators

The evaluation of each alternative strategy within the case study is associated with its performance against the following metrics:

- total savings in water consumption;
- savings in potable consumption;
- savings in non-potable consumption;
- savings in wastewater generation;
- reductions in rainfall runoff;
- improvements in runoff quality;
- reductions in (external) water supply (supply other than rainwater, local groundwater or water recycled through water mains);
- reductions in energy use (also associated with CO_2/greenhouse gas emissions).

It should be noted that although these indicators measure different aspects of the strategies' performance they should not be added up, as that would result in double counting of some flows.

3.7 Main Assumptions

Indoor water use is assumed to be constant throughout the year. No day-to-day and household-to-household variation is considered. Water leakage is neglected. The amount of wastewater produced is assumed to be 94% of the water consumed (Butler and Davies 2000).

Costs are not included in the comparisons. This is because costs are dependent on economic, market and regulatory conditions, which are highly variable and are associated with incentives and policies, assisting or hindering implementation. The strategies were thus assessed from a purely technical viewpoint, to provide the basis for context-specific policy formulation.

The performance of the strategies is discussed with respect to the indicators detailed above and set against the benchmark (Strategy 1).

4 Performance Assessment

The strategies identified above underwent an assessment based on available literature and communication with experts to provide a broad-brush comparison of their key strengths and weaknesses. Literature values and expert assessments were included in the "technology library" of the Urban Water Optioneering Tool (UWOT, see Makropoulos et al. 2008a, b) and used to model the case study's urban water system. Additional results post-processing was undertaken to account for variables that are not included in UWOT (such as energy recovery using plants). The analysis did not aim to provide accurate figures for the prioritisation of the strategies, which, as described above, are not directly comparable. Rather, it aims to illustrate the magnitude of the gains and improvements, as well as to illustrate the anticipated trade-offs (such as between water and energy). In that respect, the figures are purely *indicative* and should not be quoted as accurate *predictions* of strategy impact. The actual impact of the strategy would depend on a number of additional parameters, including the site-specific, context-related characteristics of a given development, as well as the actual resource constraints and requirements.

4.1 Strategy 1: Benchmark

4.1.1 General Assumptions

Assumes current practice, with all services sufficiently centralised, and is guided by the 2002 UK Building Regulations. These suggest that metering is applied to all properties and 6-L toilets employed, with minor SUDS for stormwater control.

4.1.2 Reductions in Mains Water Supplied and Wastewater Generated

All water consumed is centrally treated to potable standard with an average consumption of 145.6 L/capita/day. Wastewater generation is at 136.8 L/capita/day. These figures assume the implementation of both metering and 6-L toilets (2002 UK Building Regulations) and could even be considered to slightly underestimate consumption. This is considered a cautious estimate, providing a higher benchmark for the strategies comparison.

4.1.3 Greenhouse Gas Reduction/Energy Use

Energy use is associated with water treatment (assumed to be 700 kWh/ML) and wastewater treatment (assumed to be 820 kWh/ML). Clearly the exact figures vary from case to case, depending on topographical characteristics and distance, which are closely associated with pumping cost. However, the figures used in this study closely match average values used in the literature (see for example Balkema 2003).

4.1.4 Stormwater

The main assumption here is that only impervious areas contribute to runoff, while evapotranspiration is not taken into account. Since some SUDS are deployed (mostly inlet control and pervious surfaces) within this case, stormwater flow is attenuated. It is assumed that 30% of the flow from roof surfaces is discharged to pervious surfaces. Stormwater runoff is thus significantly reduced and some improvement in stormwater quality is anticipated.

4.2 Strategy 2: Next Step

4.2.1 General Assumptions

Water conservation increases. Demand management through water saving devices and ‘smart’ metering is added to strategy 1. A potable/non-potable water distinction is made, with alternative non-potable water sources used at community level. Stormwater management is increased through the use of more source control measures and onsite underground storage. In addition, stormwater quality becomes an important issue, with the inclusion of low-tech quality improvement options.

4.2.2 Reductions in Mains Water Supplied and Wastewater Generated

There is a significant reduction in the amount of potable water used in relation to the benchmark. This is due to the use of water saving devices (achieving a 25–30% reduction in demand) and of the distinction between potable and non-potable water, such that potable water previously used for WC flushing and outdoor uses is replaced with non-potable rainwater. The application of water saving devices also results in a reduction in total water use and a corresponding reduction in wastewater generation.

4.2.3 Greenhouse Gas Reduction/Energy Use

In relation to the benchmark, strategy 2 uses less energy, in line with the reduction in water consumed. It is associated with the reduced energy requirements for water and wastewater treatment. This is despite a rather cautious estimate of 3,000 kWh/ML for energy use related to the rainwater harvesting system. Although this value is consistent with examples from the literature (Legget et al. 2001), it should be noted that these examples are at a much smaller scale than predicted in this case and actual energy consumption for community/large house clusters should be lower.

4.2.4 Stormwater

Further SUDS implementation results in a 50% reduction in impermeable areas. Stormwater quality is also a priority and a 65% reduction in total suspended solids (TSS) is achieved by passing all collected stormwater through water quality polishing SUDS.

4.3 Strategy 3: Limited Central Infrastructure

4.3.1 General Assumptions

In this case, the existing infrastructure is limited both in terms of water supply and, more importantly, wastewater collection and treatment capacity. Increases in the use of recycling and onsite treatment at community scale are envisaged. Potable water is supplied as in strategy 2, but non-potable water supply is derived from greywater recycling. Very low flush toilets are deployed to minimise water use.

4.3.2 Reductions in Mains Water Supplied and Wastewater Generated

Greywater is used to supply non-potable water needs. Savings in potable water are similar to strategy 2 due to the potable/non-potable distinction, although the non-potable supply is now more secure as it is guaranteed by the consumption rather than being reliant on climatic conditions. There is a reduction in non-potable water demand due to the very low flush toilets that are being employed. Consequently, this alternative has a much lower total water use and results in a greater reduction in wastewater generation.

4.3.3 Greenhouse Gas Reduction/Energy Use

The strategy assumes an energy use of 4,000 kWh/ML for the greywater treatment system (Balkema 2003), which is also consistent with Legget et al. (2001). This is a conservative value as experience with community scale greywater treatment is scarce and most quoted values relate to smaller scale greywater treatment facilities, which cannot utilise economies of scale.[1] It also assumes increased energy recovery at the (central) WWTP, using anaerobic processes (from 20% to 55% of the full energy potential). This is a reasonable assumption due to: (a) the link to a central WWTP (as opposed to strategy 4); and (b) the increased strength of the wastewater (as opposed to strategies 1 and 2). It has a somewhat higher energy use but could allow for a moderate overall net decrease in energy use for the total system due to energy recovery.

4.3.4 Stormwater

The strategy assumes the use of stormwater wetlands/ponds for stormwater control, with up to 50% of paved area runoff and 50% of roofed area runoff drained to ponds. This leads to significant improvements in stormwater quality (80% TSS reduction). Land use costs and land availability implications need to be taken into account within the context of this strategy.

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[1] Figures as low as 500–750 KWh/ML have also been quoted for large greywater treatment plants (Davies et al. 1998), which make community greywater comparable to conventional central water management in terms of energy costs.

4.4 Strategy 4: No Central Infrastructure

4.4.1 General Assumptions

This case identifies a set of technical options responding to a more constrained environment, in which both water supply and wastewater collection systems are unavailable. A potable/non-potable distinction exists here similar to strategy 3. Water-saving devices are employed, with the water treated at the point of use for both potable and non-potable applications. Bottled water is used as a back-up to the potable water system. Rainwater recycling doubles as a stormwater management technology through the use of a built-in storage system. Cesspools are used for wastewater collection and treatment is performed by willow plantations, which also generates biofuel for use in CHP plants.

4.4.2 Reductions in Mains Water Supplied and Wastewater Generated

This strategy reduces potable water consumption, coupled with a further reduction in non-potable water consumption, as compared to strategy 3. It is assumed that all water needs (including potable) are met by rainwater harvesting (and/or local groundwater), with any deficit being met by bottled water. Strategy 4 is largely autonomous from a water point of view at a community level.

4.4.3 Greenhouse Gas Reduction/Energy Use

For the potable fraction of the water supply, an energy use of 8,000 kWh/ML for the rainwater harvesting and treatment system was assumed (Balkema 2003). For the non-potable fraction, the same value of 3,000 KWh/ML was used as in strategy 2. The high energy demand for potable water is associated with UV (ultra-violet) disinfection requirements.[2] As suggested earlier, all estimates are associated with smaller scale schemes and should be regarded as cautious. This case has a higher decrease in water dependency from external sources, as well as higher energy use.

Energy recovery from biofuel production (willows) has been taken into account within the wastewater treatment approach adopted in this strategy. The strategy assumes a significant area for willow cultivation (approximately 100 ha), which is similar in size to the entire development (but well in line with known case studies). The size of the willow plantation was calculated to allow for the treatment of all wastewater produced under the strategy and the energy gains[3] are reduced by a measure of the energy requirements of transporting the wastewater to the plantation by trucks. A mean distance of 5 km was used for this calculation, together with figures available from literature (Balkema 2003).

4.4.4 Stormwater

Stormwater runoff is significantly reduced since all roof runoff is collected. A further improvement in quality is also observed, arising from the use of flow storage.

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[2] Although recent literature is suggesting that Domestic Hot Water (DHW) is also a very important fraction of total residential energy use (e.g. Ndoye and Sarr 2008).

[3] Assumed biomass-to-energy for willows: 1 kg = 1 KWh.

5 Results and Discussion

5.1 Water

The three strategies are compared in terms of the percentage improvement they can offer with respect to the benchmark (Fig. 1). In terms of water, all strategies developed have the potential to significantly improve the situation beyond the Benchmark. Compared with the current situation (existing stock), the improvements should be even more pronounced.

Strategy 2 provides an overall improvement of around 20% across many of the indicators. It also generates more substantial improvements in reducing the use of potable water (47%, of which approximately 27% comes from in-house water savings) and improving runoff water quality (50% improvement compared to the benchmark).

Strategy 3 achieves the same potable water savings, but goes further by reducing wastewater through the use of treated greywater for non-potable uses (WC and outdoor uses). The use of small-bore sewers in this strategy addresses wastewater conveyance issues that arise from this lower volume/higher concentration effluent. The anticipated change in wastewater quality is not expected to affect treatment adversely, providing that any changes at existing works are carried out gradually. The increased use of SUDS and on-site storage also provides a further reduction in runoff volume and improves runoff quality in terms of TSS.

Strategy 4 focuses on water autonomy and has the potential to produce a very significant decrease in external water supply (between 80% and 100%, depending on rainfall patterns, availability of groundwater and storage). Issues of security of supply resulting from this kind of reduction are mostly site-specific and relate to the economics of providing a back-up water supply network or relying on bottled water for situations where supply does not meet demand. These would need to be addressed on a case-by-case basis. The slight increase in potable water savings observed in this strategy (also mirrored in the total water consumption savings)

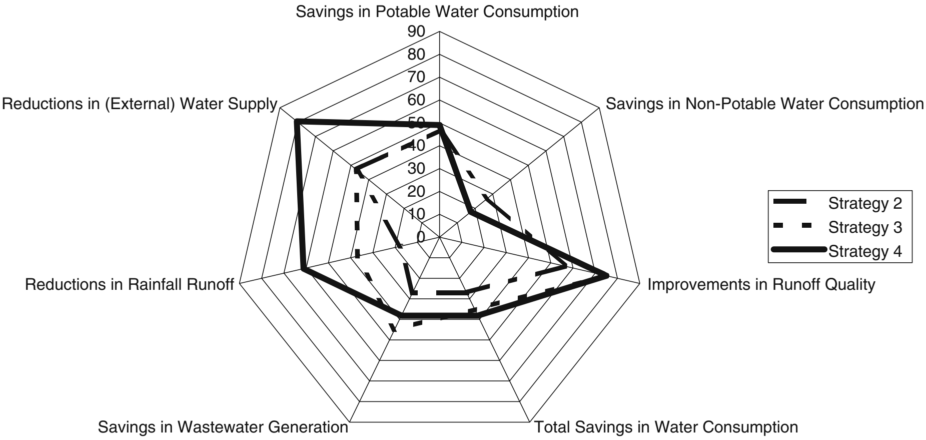

Fig. 1 Strategy comparison in terms of water (as percentage improvement from benchmark)

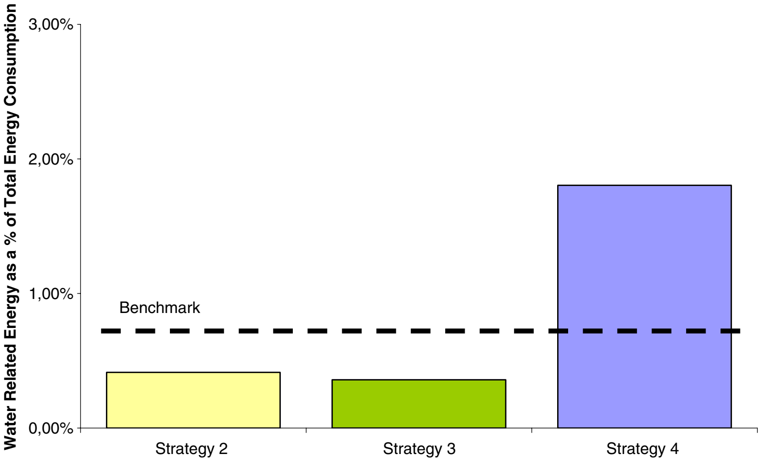

Fig. 2 Strategy comparison in terms of energy (as a percentage of total household energy consumption)

compared with strategy 2 and 3 comes from ultra-low water using toilets, which are required because of the lack of a wastewater conveyance network. Due to the extensive use of rainwater as both a potable and a non-potable source, this strategy also demonstrates the greatest potential for runoff reduction. In all other respects, the strategy performs at least as well as the best prior strategy, with the exception of wastewater from in-house uses, in which it is inferior to strategy 3, based on greywater treatment and reuse.

Strategies 3 and 4 demonstrate the greatest potential savings in water consumption, with the notable difference that strategy 4 draws (most of) the water required from local sources while strategy 3 relies on a central water supply. Both strategies also address emerging concerns about wastewater treatment capacity becoming the limiting factor for new developments.

5.2 Energy

In terms of energy (Fig. 2), strategy 2 demonstrates an improvement of 30–40% compared to the benchmark,[4] due to the reduced requirements for water and wastewater treatment. This is despite the energy requirements for rainwater harvesting (which are mainly associated with pumping costs). Strategy 3 demonstrates a 40–45% reduction compared to the benchmark, despite the significant (pessimistic) energy requirements assumed for greywater recycling. Strategy 4 indicates a substantial increase in per capita energy consumption due to the significant energy costs

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[4] In the benchmark strategy, urban water related energy consumption is calculated as approximately 0.8% of the total household energy consumption, based on an average household energy consumption figure of 24.4 KWh/h/day (Shorrock and Utley 2003b).

associated with point-of-use water treatment. There are, however, a number of issues that need to be stressed.

- The assumed energy requirements for treating rainwater to potable standards should be considered as an upper boundary. This is because information was limited to rainwater harvesting systems at a much smaller scale than the one assumed for strategy 4. Literature suggests that treatment costs (including energy) should be expected to decrease as a function of increasing application scale, while conveyance costs remain almost constant with scale (Friedler and Hadari 2006).
- Waste-to-energy systems other than willows (such as combined solid waste and wastewater composting systems) could potentially give a higher energy return than the approach assumed in strategy 4. Most of these systems are in prototype stage and more research is required to determine their true potential.
- Although land availability is important in strategy 4, it does not necessarily result in a reduction in the land available for development, since energy plants could potentially be cultivated in land set aside for other (non-urban development) uses (for example, sacrificial land set aside as part of a flood management strategy).
- The energy requirements of strategy 4, although higher than the other strategies, are still small compared to average UK household energy requirements. Water-related energy for strategy 4 is around 1.8% of average household consumption, compared to 0.8% for the benchmark (see also Shorrock and Utley 2003a).

A general point that emerges from comparing the strategy is that there are trade-offs between water use, energy use and land use, and these have an equilibrium point that is associated with the technological state-of-art. At a given technological state-of-art, further reductions in water savings signify increases in either energy consumption (for high-tech solutions) or land use (for low-tech solutions). The strategies indicate that until this equilibrium point is reached (as in strategy 2: Next Step) there can be significant gains in all three aspects. After this point (as in strategy 3: Limited External Infrastructure, but more importantly in strategy 4: No External Infrastructure), improvements in one aspect signify costs in others. The choice of desired trade-off then depends on the specific constraints of the problem at hand. If the wastewater system is close to capacity, then greywater recycling (strategy 3) can alleviate the problem substantially. If additional water resources are unavailable or the development is a significant distance from existing infrastructure, more autonomous solutions (such as strategy 4) can be investigated, at the expense of either energy or land use.

6 Uncertainties

As suggested, the figures used for this broad brush analysis are purely indicative and, as such, capture only some of the issues associated with distributed infrastructure. In particular, issues regarding boundaries of analysis (limiting calculations to the house level, the development level, the regional level or the national level) have not been explored.

The uncertainty is higher where estimates require links to other systems, with energy being the prime example. Much of the uncertainty stems from the fact that applications of rainwater harvesting and greywater recycling at a community scale are rare, even at the international level. A more detailed study should carefully screen the few examples that are available (the most notable of which have been reported in this paper), in order to extract case-independent characteristics that can be used as meaningful predictors of the systems' performance and costs.

7 Future Research Needs

The alternative strategies discussed above (as well as other possible ones) represent responses to constraints faced by new urban developments when located within a given environmental, social and infrastructural context. It is suggested that, prior to locating new urban developments, the carrying capacity of the existing infrastructure and the local environment at a strategic level should be taken into account. Work on this issue has recently been undertaken (see for example Butler et al. 2005), but more effort is required to increase the scope and uptake of such initiatives and tools within the strategic planning process and its link to stakeholders (Pearson et al. 2010) including end users at the household level (Chu et al. 2009).

There is a considerable knowledge gap in terms of the performance and operational costs associated with community level infrastructure, including, but not restricted to, communal greywater treatment and rainwater treatment facilities to both potable and non-potable standards (Sharma et al. 2009). This knowledge gap is primarily due to the unavailability of real world examples of the application of such technologies and the extent to which costs are case specific.

Issues relating to the effects on existing infrastructure of changing the quantity and quality of wastewater and stormwater also need to continue to be on the research agenda for some time (see also: Parkinson et al. 2005).

Furthermore, there is a clear need to investigate the interactions between water, energy and waste streams within the urban environment and to identify potential gains from their integration at a distributed level. The issue of distributed energy production, as well as the issue of distributed solid waste management, may present interesting new possibilities concerning the viability of distributed water infrastructure, by extending further the equilibrium point of the water–energy–land trade-off (Koutsoyiannis et al. 2009; Odhiambo et al. 2009).

8 Conclusions

Technologies for managing urban water at the regional level are well understood, with case studies and operating data gradually emerging. Furthermore, technologies for managing urban water at the household level, although having a shorter track record, are a subject of emerging interest and on-going research. In contrast, distributed water infrastructure (placed at the community scale) is relatively untried and unproven. This work presents an overview of some of the available knowledge and illustrates the potential impact of both local, but also community level water infrastructure through the use of a number of alternative (technological) strategies.

The paper summarises the main categories of both centralised and decentralised water infrastructure, covering all three flows (water supply, wastewater and drainage) and their integration through recycling and reuse. The potential impact of the identified infrastructure options on urban water management was examined through the selection and assessment of indicative infrastructure strategies. These strategies aimed at:

- selecting a number of compatible technology sets across the urban water flows, with an emphasis on distributed solutions;
- illustrating the potential impact of these technology sets on water management under a number of realistic and more radical constraints.

The selection of these technological sets does not imply that other similar sets could not be viable. Indeed, there are numerous permutations of the identified technologies. This paper has simply attempted to examine likely alternative strategies for distributed infrastructure deployment, rather than to enumerate all the possible alternatives. Strategy 2 is the most realistic and, as such, is offered as a possible 'next step'. Strategies 3 and 4 are more radical and attempt to identify technologically feasible options for addressing water infrastructure constraints, which may appear in the context of specific future urban development projects. The desirability of these options is a function of a series of constraints, including water resource availability, treatment plant capacity, cost of upgrading the infrastructure, developments in (distributed) energy (micro) generation and climate change.

Assessment of the strategies is only indicative, as the performance of the technological options is associated—to a large extent—with case-specific characteristics and cannot be easily generalised. It shows, however, that there is significant potential for a range of improvements in urban water management (reduction in potable water demand, reduction in wastewater generation, reduction in runoff, improvement of water quality) resulting from the context-aware deployment of a portfolio of technological infrastructure options (including in-house, decentralised and centralised options).

Issues of interaction at the local scale, between water infrastructure and energy and waste infrastructure, have not been addressed in detail within this paper. A more detailed analysis of these (and other) options should be undertaken to examine issues relating to the distribution of impacts at multiple scales. It should also examine issues regarding the whole life cycle of the distributed infrastructure, which could not be covered in this work.

The work has identified the following research needs in the following areas:

- On the performance and operation (including energy) of community level infrastructure, including, but not restricted to, communal greywater treatment and rainwater treatment facilities to both potable and non-potable standards.
- On the effects of changing wastewater and stormwater quantity and quality on existing infrastructure.
- On issues regarding the context-aware strategic planning of new urban developments and the appropriate combination of (proactive) site selection and (reactive) response to given contexts.
- On the interactions between distributed water, energy and waste infrastructures, which may become very important for the viability of each other at the local/community level.

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