Urban Water Reuse: A Triple Bottom Line Assessment Framework and Review

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Abstract - Water reuse networks have been emerging globally for the last 50 years. This article reviews the economic, social and environmental issues related to implementing water reuse networks in cities. This is reflecting the fact that globally many cities are categorised as water scarce areas, where there is growing imbalance between water demand and availability. In this sense, there is a need for sustainable water supply solutions in the imminent future to provide and maintain service reliability, particularly in the face of climate change. To demonstrate the sustainability implications of water reuse practices, we review a case study in London, UK.

Keywords: Water reuse; decentralised water supply; integrated urban water management; water scarcity; public health; climate change

1. Introduction

Water reuse networks have been emerging globally for the last 50 years; firstly in Japan (Asano et al., 1996; Ogoshi et al., 2001; Suzuki et al., 2002) in response to long-term droughts, and more recently in Australia (Dolnicar and Hurlimann, 2010; Moglia et al., 2011) to diversify their water supply portfolio and to improve water supply resilience.

More than 50 years ago, Abel Wolman predicted the need for an urban scale water reuse in his seminal article 'The Metabolism of Cities' (Wolman, 1965). By drawing

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an analogy between the nutritional flows of a metabolic being and the resource flow of a city, he suggested that in order to maintain levels of water consumption at 1960s American levels, combined with the anticipated population growth, a portion of the water supply could be most economically met through recycling. The resemblance between his options for future water provision, which include inter-regional water transfer and those present in modern urban infrastructure feasibility plans is indicative of the complexity of the balance between population, abstraction and pollution. Then, as now, no single infrastructural system can be implemented as a panacea.

Water recycling is becoming more common as the perception about the local and regional hydrological environment of cities is evolving and the need for Integrated Urban Water Management (IUWM). IUWM concerns a transition towards a more sustainable solution for water, sewerage and storm water systems. Within IUWM, there is a trade-off between water, energy and land use, where the optimal solution is a balance between hi-tech (energy intensive) and lo-tech (land intensive) forms of supply and treatment (Makropoulos and Butler, 2010). As a component of IUWM, water reuse presents an opportunity to increase the stock of available water at a lower marginal cost and improved environmental and social outcomes (Nasiri et al. 2013).

Decision making about urban water infrastructure projects is complex. There may be an array of available infrastructural and technological options to choose between. Decisions need to account for interdependencies between existing infrastructures, complex hydrologic, economic, environmental, financial, institutional, and social conditions, and water, land and energy use constraints. The very unique local characteristics and requirements of any water reuse project mean that no single combination can be recommended as a panacea.

Globally, interactions between localised political, environmental, social and technological factors have resulted in the development of diverse urban water recycling infrastructural arrangements (Asano et al., 1996; Suzuki et al., 2002). In the arid areas of Middle East and North Africa, wastewater is commonly reused for urban irrigation (Banks, 1990; Khouri, 1992; Jimenez et al., 2008). In Japan, dense urban areas without reliable water sources have required the development of innovative dual reticulation systems, where wastewater is reused (from sink to toilet flush), within buildings, districts, and cities (Asano et al., 1996). . In California, high per capita water demand in densely populated cities has led to indirect potable reuse of wastewater (Nellor, 2009). Wastewater is treated to a high standard, pumped underground to replenish groundwater aquifers, subsequently abstracted, and transmitted as potable water.

This paper addresses the economic, social and environmental issues related to implementing urban water reuse networks (Figure 1). Following a triple bottom line analysis of the sustainability of urban water recycling, we address the policy and regulatory requirement to support transition sustainable urban water reuse. The

BedZED housing development in London, UK, is presented as a case study of district scale reuse network. The paper concludes with a discussion, summarising the sustainability considerations, challenges and opportunities surrounding water reuse implementation in cities.

2. Economics

2.1. Project Feasibility

Although the terms are often used interchangeably, the economic and financial viability of a water reuse project are two separate concepts. A water reuse project can be deemed economically beneficial if after considering all externalities the sum of its benefits exceeds the sum of its costs; while it can be considered financially viable only if sufficient financial resources and mechanism exist for its implementation (Asano et al., 2007). Projects which maximise economic benefit and adhere to financial constraints are the most rational to implement. It should be mentioned that benefits and costs of a water reuse projects are to be established through a whole life benefit-costing, where estimations incorporates design, planning, construction, operation, and decommissioning of facilities (Fane et al, 2002). Such a model accounts for decision alternatives in terms of project location, capacity, operational and maintenance conditions, choice of technologies, environmental requirements and other aspects that will be discussed in the following sections.

2.2. Markets

The characteristics of local water markets determines the feasibility of a water reuse scheme (Hochstrat et al., 2007), structuring the related financial constraints. Subsidies for schemes can help to address inequalities and externalities that are present in the market and to create financial viability. Although most existing schemes are subsidised (Hochstrat et al., 2007), generally the lack of funding has been identified as a major barrier to widespread implementation (Bixio et al., 2008). This contributes to the lack of large scale pilot projects that could provide sufficient information, knowledge and experience to enable and encourage investors to get involved in this practice.

The peculiarity of local water market conditions surrounding reuse schemes make it almost impossible to compare these projects as construction, maintenance, technology, and costs vary significantly. Whilst schemes cannot easily be compared in quantitative terms across locations, the financial viability of a project can be assessed in comparison to existing urban infrastructure. Furthermore, the unit cost can be used to compare alternative water sources and supply systems such as desalination and indirect, direct or non-potable reuse (Nasiri et al. 2013). This will establish a benchmark of break-even points for alternative water reuse practices, identifying where and under what local conditions these options are economically preferable.

2.3. Technologies

Based on the type of contaminant in waste water, different sewage collection lines are designed for common households and office buildings, particularly for the effluents known as greywater and blackwater (Bertrand et al. 2008). Greywater is produced in domestic applications, such as showers, baths and, washing machines, which has fewer pathogens yet greater amounts of soaps and other household chemicals (Keely et al. 2015). Blackwater on the other hand is the waste discharged from the toilet, and contains mainly feces and urine, substances that are hazardous to human health and need to be handled in a prescribed manner (Zeng and Mitch 2015). Physical and chemical treatments could be applied to both types of waste to produce low quality, non-potable water. Since both of them contain mainly organic waste (Antonopoulou et al. 2013), enhanced purification, such as membrane filtration and biological treatment are also necessary to produce higher quality potable water.

Making up 50~80% of household sewage (Blair 2014), greywater is considered as an ideal lower-grade water source (Ushijima et al. 2014). Suitable treatment driven methods should be employed to effectively treat the greywater for reuse in different purposes. Minor treatments, such as sedimentation and sand/soil filtration (Ushijima et al. 2015) effectively offer non-potable water that can be used in landscape irrigation because of the lower water quality requirements for use on grass and plants. As well, plant-bed could benefit from the remaining nutrients found in the greywater, such as nitrogen, phosphorous and potassium (Khan et al. 2013). To recycle water for application in human hygiene such as showering or flushing toilets, a combination of aerobic digestion and membrane filtration (Schäfer et al. 2006) (e.g. ultra-filtration, microfiltration) could be used for the removal of organic containments and bacteria. Among them, sequencing batch reactor (SBR) (Gabarro et al. 2013) and membrane biological reactor (MBR) (Jefferson et al. 2001) techniques have been widely reported as effective methods in the greywater recycling process. To further improve the water quality to produce water deemed potable, the combination of the above-mentioned pre-treatments with nano-filtration (NF) (Ramon et al. 2004) or reverse osmosis (RO) process (Šostar-Turk et al. 2005) and chlorine/UV disinfection is a commonly reported method.

Blackwater is considered hazardous under normal circumstances (Fidjeland et al. 2015). The septic tank system (Brandes 1978), which contains sedimentation and light filtration, is one of the most facile ways to reclaim blackwater. From the septic tank, effluent could be used for subsurface irrigation, while elaborate treatment processes should be employed for the treatment of the condensed sludge. A combination of aerobic and anaerobic digestion is a traditional method to remove the large quantities of TOC (total organic carbon), TN (total nitrogen), TP (total phosphorous), and pathogens in blackwater (Luostarinen and Rintala 2007, Mes et al. 2007). Upstream anaerobic sludge bed (UASB) has great potential for the precipitation of phosphate, as well as reduction of pathogens and bacteria. Therefore, it is already widely used as a practical blackwater treatment process (Luostarinen et al. 2007). After biological treatment and chlorine/UV disinfection, the blackwater could be used as low-level-contaminated greywater, and be piped to applications such as in cooling towers or car washes (Paulo et al. 2013). To produce potable water from a blackwater source, advanced treatments, such as RO filtration and adequate disinfection process are essential to make the water clean enough; while the expensive equipment, costly maintenance, and the acceptance by the public are just some of the challenges to make application possible (Boulware 2013).

2.4. System and Network

There are numerous examples of water reuse systems, which are mainly categorised as centralised and decentralised. Centralised systems serve a number of potable and non-potable applications including agricultural irrigation, industrial cooling, environmental restoration, groundwater recharge, surface-water augmentation and urban reuse. Applications for water reuse reflect the varying economic, social and environmental drivers for the adoption of an alternative water supply system. In arid regions, reclaimed water is generally applied in agriculture, in contrast to urban areas in the US, Asia and Australia, where municipal demand has encouraged the development of potable and non-potable reuse. Examples of non-potable reuse can be found in cities such as Sydney, Adelaide, Tokyo and New York. Potable reuse is less common, currently practiced in Singapore, Orange County, California, Windhoek, Namibia, and Big Springs, Texas and under development in cities including Perth and London.

Large-scale systems benefit from economies of scale in management and treatment costs but require significantly larger capital and operational investment in distribution systems, to convey water over larger distances than decentralised systems. This is particularly critical for non-potable reuse which requires a dual reticulation system. Following a series of severe drought seasons, Japan has developed reclaimed water as a significant source for predominantly non-potable environmental (45%) and industrial (24%) applications. Of particular note is Fukoaka City which has a 4500 m^3/d reclamation plant supplying water for toilet flushing, park irrigation, and commercial buildings through a dual-reticulation system, which came online in 1980 (Suzuki et al., 2002).

Centralised municipal reuse schemes have generally favoured potable applications. Direct potable reuse has emerged as a potential option due to gains in treatment technology and lower costs compared to alternative schemes associated costs (Hochstrat et al., 2007; Crook, 2010; NWRI, 2010; Leverenz et al., 2011; Tchobanoglous et al., 2011). Direct potable reuse avoids the costs associated with the development of an environmental buffer in indirect potable reuse and those of a dual-reticulated network for non-potable reuse. These benefits have contributed to the implementation of direct potable reuse in Big Springs and plans for a similar scheme in Witchita Falls and Brownwood, all cities in Texas that faced extended drought conditions in recent years.

Decentralised water systems, on the other hand, refer to a range of technologies and infrastructure that can be used as an alternative water supply method. The scale and integration of systems varies considerably from: individual households, clusters of buildings, to suburbs and districts. In addition, systems can operate outside of centralised services independently or integrated within as satellite components (Gikas and Tchobanoglous, 2009). Decentralised systems can make use of a number of different sources of water; these include: rainwater, storm-water, greywater and locally reclaimed water (Moglia et al., 2011). Australia has emerged at the forefront of research and implementation of such systems (Tjandraatmadja et al., 2005; Sharma et al., 2008; Cook et al., 2009). Decentralised systems can provide the opportunity for a number of benefits; cost reduction, resource efficiency, service security, system failure reduction, local economic strength, community wellbeing, and environmental protection (Biggs et al., 2008).

Perhaps the biggest challenge facing the implementation of decentralised systems is the lack of empirical information depicting system success and failure (Moglia et al., 2011. In particular there are no available studies concerning the implementation of decentralised systems at full system scale, although several consider projects at development scale (Burn et al., 2012). Other significant challenges include institutional barriers (Sharma et al., 2010), public concern (Moglia et al., 2011), construction (Moglia et al., 2011) and system complexity (Novotny et al., 2010).

In the realm of decentralised systems, limited information from cluster and neighbourhood scale schemes (Clerico et al., 2007; Verrecht et al., 2012) suggest that small-scale decentralised wastewater reclamation is not yet as economically efficient as traditional mains and sewer infrastructure. However, these schemes have demonstrated that cluster and neighbourhood scale reuse remains a novel and emerging approach to the provision of water and treatment of wastewater, as they are still hard to operate optimally. In particular, results from BedZED (Verrecht et al., 2012) show that maintaining a balance between public acceptance and water quality, staff maintenance costs and technological capital costs, treatment efficiency gains and capital storage costs, and storm-water, rainwater and reclaimed water integration is difficult. The trade-off between the treatment efficiency gains associated with attenuated large-scale centralised systems and the costs associated with distribution of combinations of potable, non-potable and wastewater are uniquely complicated in different neighbourhoods.

3. Society

3.1. Public Perception and Participation

The public perception of any urban infrastructural system is integral to its success; without their support, the system may be under-utilised or rejected. The form that water and sewerage systems take in modern cities conforms to the requirements of its municipal and industrial users in the sense that it provides a delivery and removal service that is seemingly instant and limitless. When the water and sewerage system reaches its hydrological limits, this service model is challenged and the perceptions of any system modifications or novel technologies are critical to its success.

Community involvement in urban water reuse decision making can take several forms: where design stems from public requirements and perceptions (Bell, 2012); public participation in planning (Asano and Bahri, 2010); or the presentation of a situation where no viable alternatives exist (Dolnicar and Hurlimann, 2010). Public resistance to the introduction of water reuse schemes can be viewed as either an obstruction or as a failure to adequately assess user requirements and perception.

Public reaction to schemes in Australia has been both well documented and studied and has shown some major concerns that include the perceived risk to public health; the potential for system failure; the chemical and biological composition of water; and environmental issues (Dolnicar and Hurlimann, 2010; Moglia et al., 2011). Objection to water reuse has been shown to increase as the use of water moves closer to the body (Dolnicar and Hurlimann, 2010).

In the UK in 2008 a survey of customers of water utility Thames Water indicated a higher level of acceptance of the concept of potable reuse than in most other studies in other countries (Aitken et al. 2014). Overall, 60% of respondents in London and the Thames Valley indicated their support for planned potable reuse, compared with 59% in San Diego in 1993 and 42% in Tampa in 1996 (Marks, 2006), 26% in Sydney in 1999 (Marks et al., 2006), 31% Perth in 2004 (Po et al., 2003) and 41% in Australia (Marks et al., 2006).

3.2. Water Quality and Public Health

The conditions which brought about the sanitary revolution in the 19th century were combined knowledge of water quality, public health and urban population density. The resulting infrastructural system recognised the need to divert pollutant flows in order to protect drinking water quality and public health. Emerging forms of water reuse – whether potable or non-potable – are an evolution from the linear anthropogenic hydrological cycle. Closing this cycle brings new dimensions of safety and control to water quality and public health.

Widespread pollution of watercourses used for potable water abstraction has blurred the boundaries in treatment between all forms of potable reuse, planned and unplanned, and direct and indirect. There are, however, variations in the definition of safe water, moving from the ‘concept of pathogen free water’ towards one which is fit for consumption (Rose, 2007).

Two notable frameworks by the US EPA (EPA, 2004) and WHO (WHO, 2006) have addressed acceptable water qualities for different applications by proposing guidelines for the safe reuse of water in the public domain. The EPA guidelines are used in US states without their own regulatory criteria (excluding California and Florida which have their own standards for water reuse) as a benchmark for assessments (US NRC, 2012). They have also been used in the UK (Verrecht et al., 2012), where a regulatory standard for water reuse does not exist.

Many factors may influence the determination of an acceptable water quality for a particular application, where maintaining a balance between cost and public safety function as the principle constraint. The recent advancement of direct potable reuse has highlighted the need to safety requirements incurred by the removal of an environmental barrier as the result of water reuse schemes (Crook, 2010). These requirements are associated with reclaimed water quality, barriers and monitoring capacity, and system operation, reliability and administration.

4. Environment

Modern engineering has allowed the emergence of the anthropogenic hydrological cycle (Hochstrat et al., 2007) – abstract, use, collect, purify, and discharge. Infrastructure systems now provide an urban form which is no longer determined by hydrological cycles (Teh, 2009) and have enabled cities to partially disconnect themselves from the constraints of the natural environment. As a result, many cities now exist beyond the limit of the local hydrological systems upon which they rely (Bell, 2012) due to the adoption unsustainable practices. Critically, this anthropogenic cycle hides its own existence to the extent that whilst water is perceived to be both plentiful and impeccable (Sofoulis, 2005), citizens are almost unaware of the mechanisms by which their waste is removed (Novotny et al., 2010).

Modern urban water supply has reached a point where resource and environmental constraints present the need for alternative solutions (Bell, 2012). Water reuse presents three obvious opportunities to reduce environmental impact over conventional water supply and treatment (Anderson, 2003): a reduction in the need for freshwater diversion (reduced abstraction); a reduction in the levels of pollutant discharge (reduced discharge); and improved downstream water quality (greater dilution of pollutants). These benefits combine to improve conditions for the inhabitants of surrounding ecosystems.

The environmental implications of water reuse have been observed and discussed mostly with respect to (Asano et al., 2007): alterations to the water table and river levels from excessive irrigation with reclaimed water; alterations to soil composition through chemical pollution and micro-organisms; and eutrophication with potentially toxic algal blooms. Therefore, as reclaimed water has a different constitution to native freshwater, the benefits resulted from its applications can be maximised by understanding the ways in which it will modify its host environment.

5. Transition to Urban Water Reuse

Adaptive governance mechanisms enable the capture of knowledge required to overcome the institutional and technical challenges to industrial capacity building. These measures include performance monitoring, identification of key success factors, stakeholder discussion, complexity understanding, and flexible institutional mechanisms (Moglia et al., 2011).

The technological transition to widespread adoption of water reuse requires successful pilot schemes and demonstration projects that are protected from conventional market factors in niche environments referred to as ‘incubation rooms’ (Geels, 2002). These protected environments may also provide society with the opportunity to test the operational performance of decentralised water reuse systems (Dolnicar and Hurlimann, 2010).

Regulators and policy makers have an important role in ensuring the long-term regional sustainability of water resource management practices in cities (Obeng et al., 2010). The economies of scale inherent in urban water supply and the monopolistic provision of services by water utilities creates an environment which is naturally conducive to the establishment of the niche markets (Geels, 2002) in which water reuse networks could emerge. The outcomes of policies and regulations that are encouraging water reuse can be seen in Japan (Asano et al., 1996; Suzuki et al., 2002). In Europe, the EU Water Framework Directive (EU, 2000) provides a stimulus for the development of municipal wastewater reuse by requiring the development of an integrated water management plan which incorporates previously isolated components of urban water supply (Bixio et al., 2008).

Regulating water reuse systems is crucial for the protection of public health; but is globally inconsistent, being symptomatic of local constraints. Water quality standards are controlled at the state level in the United States rather than by the federal government. This has led to contrasting regulatory requirements (US NRC, 2012), particularly in Florida and California (CDPH, 2009), two states with an established reclaimed water sector. In addition, this has acted as a barrier-to-entry in other emerging regions that lack proven standards to enhance public confidence (Nellor and Larson, 2010; US NRC, 2012). In situations where national regulation for water reuse does not exist, the US EPA guidelines (EPA, 2004) are often applied, as in the case of BedZED in London (Verrecht et al., 2012). The World Health Organisation (WHO) also produces updated guidelines periodically (WHO, 2006) with a particular emphasis upon maximising the public health benefits of water reuse, principally in irrigation and agricultural applications.

5.1. Direct Potable Reuse

Until recently direct potable reuse (DPR) was known only in Windhoek, Namibia, where low precipitation and high evaporation require the water supply to be regularly augment with reclaimed water (Du Pisani, 2006; Lahnsteiner and Lempert, 2007; Menge, 2007). Recent advances in technology and a consequent reduction of associated costs, coupled with increasing water scarcity are leading to the adoption of DPR as an alternative water supply method. Prolonged drought in the south-west of the US has resulted in propositions for DPR in Big Spring and Wichita Falls in Texas. A number of regulatory issues must be resolved before DPR can progress, including: definition of key terminology; improvement of monitoring systems; detailed assessment of health risks; establishment of an independent advisory panel; comparisons with unplanned IPR; establishment of domestic regulatory and international guideline authorities; and creation of a platform for communication and experience sharing (Crook, 2010). In particular, regulations and policies surrounding DPR must reflect the additional safety requirements incurred by the removal of an environmental barrier (Crook, 2010).

5.2. Indirect Potable Reuse

Indirect potable reuse (IPR) takes two distinct regulatory forms across the globe: planned and unplanned. Planned IPR differs from DPR in using an environmental buffer to provide further treatment and retention time. This practice is now well documented, generally taking two physical forms: the recharge of groundwater and surface water. Due mainly to the development of planned IPR in California and Florida, regulation in the US is well established. Approximately half of the US states have imposed statutory requirements for the application of IPR, with others assessing cases on an individual basis (US NRC, 2012) and based on EPA guidelines (EPA, 2004). California in particular has a well-established and discussed regulatory framework surrounding groundwater replenishment, with regulation for reclaimed water generally (CDPH, 2009) and draft regulation for groundwater recharge (CDPH, 2011).

Unplanned IPR is common in urbanised catchments and occurs when treated wastewater is discharged into the natural environment and subsequently abstracted for potable application. Due to the widespread pollution of watercourses and the presence of non-native constituents in various levels surrounding urban areas, there exists little difference between unplanned IPR and planned IPR in many contexts. Unplanned IPR is generally subject to the same regulatory conditions as non-reuse sources, which has led to the possibility of developing common water quality requirements for both reuse and non-reuse sources, reflecting treatment requirements of both sources.

5.3. Non-Potable Reuse

Non-potable reuse (NPR) is more common at a decentralised level due to the requirements for construction of a third pipeline network. However, urban reuse networks are well established in Japan following policy requirements for buildings, particularly in Tokyo and Fukuoka (Asano et al., 1996; Suzuki et al., 2002). More recently the Queensland government in Australia has introduced mandatory requirements (DIP, 2009) for on-site water reuse devices in new build homes (Mankad, 2012). The emergence of NPR in Australia has resulted in recognition of the need to develop regulatory and practice guidelines for both reclaimed water network construction and use (Sharma et al., 2010). Adaptive governance mechanisms help to gain knowledge in pilot water reuse projects through developing operation and management models, engineering design codes, installation guidelines, risk assessment frameworks, and technology selection methods (Moglia et al., 2011).

5.4. Industrial Reuse

Industry is a major user of reclaimed water. Cooling and process water recycling accounts for approximately 30% of all water reuse applications (Van der Bruggen, 2010). The proximity of industry to urban areas presents an opportunity for the recycling of municipal wastewater in industrial applications. Industrial reuse can be encouraged by increasing wastewater discharge taxes, introducing the progressive use of alternative water sources as a requirement for abstraction permits, and encouraging the development of technologies which can remove a wider range of contaminants than conventional wastewater treatment (Van der Bruggen, 2010).

6. Case Study: BedZED, London, UK

The South-East England, including Greater London, is a water scarce region (Angelakis and Bontoux, 2001; Chance, 2009). Water reuse has recently been considered as a future sustainable water supply option in the UK (UKWIR, 2005).

Beddington Zero Emission Development (BedZED) is a mixed-use sustainable housing scheme in south London, conceived by the BioRegional Development Group and Bill Dunster Architects. The development was completed in 2002 through collaboration between The Peabody Trust (the client), Arup (the design team) and the London Borough of Sutton (the original landowners). It consists of 100 homes, ranging from one bedroom apartments to 4 bedroom houses. Half of the homes are owned by the housing association, Peabody Trust, and are available to low-income people and families at affordable rent. The other half were sold on the open market at 5-10% more than similar sized houses in the area. The development also includes office space, a college and community facilities.

South London suffers from two localised water problems: flooding, largely due to a high proportion of impermeable surfaces combined with under-capacity drainage systems, and water stress, due to an imbalance between rainfall and population growth (Chance, 2009). In response to this, Arup, Bill Dunster and BioRegional devised an integrated water management strategy for the development.

BedZED's initial target was to achieve Level 6 of the UK Code for Sustainable Homes (DCLG, 2006), requiring a 50% reduction on average potable water demand for the area, bringing it to below 80 litres per day. A four part water management strategy was developed which consists of water efficiency, awareness and monitoring, rainwater harvesting, and on-site wastewater reclamation and reuse for non-potable applications (Twinn, 2003).

The majority of reductions in potable water consumption at BedZED have been due to the implementation of water-saving appliances. These include dual flush (2/4 litre) toilets, reduced flow taps (3 litres/minutes), reduced flow showers heads (11 litres/minute), and visible meters which encourage residents to observe, monitor and regulate their consumption. Records show an average water consumption of 72 lpd, with variation between 70 and 80 lpd correlated to seasonal intensity (BioRegional, 2009). BedZED have showcased the fact that it is possible to reduce potable consumption below 80 lpd with little consumer habit change (Chance, 2009) by providing water efficient appliances and a supply of non-potable water for appropriate applications. In addition to savings from appliances, potable water consumption was further reduced by an estimated 15 lpd through the use of reclaimed water for non-potable applications such as toilet flushing (BioRegional, 2009).

In its first ten years, BedZED has been host to three pilot studies on non-potable water reuse: rainwater harvesting, a biological wastewater treatment process based upon the 'Living Machine' dubbed the 'Green Water Treatment Plant' (GWTP) (Smith and Butler, 2008) run by Albion Water, and a wastewater reclamation facility, using a membrane bio-reactor (MBR) operated by Thames Water (Verrecht et al., 2012).

Both treatment processes – the GWTP and MBR – have provided a useful insight into the application of decentralised methods for water reuse. In particular, they have highlighted the trade-offs between capital costs (CAPEX) and operational costs (OPEX) when decentralised water reuse is compared with larger scale treatment plants. Both projects were found to be more expensive and energy intensive than conventional water supply, sewerage and sewerage treatment. The findings (Verrecht et al., 2012) suggest that water reuse could be economically viable if done at a larger scale (Arpke and Clerico, 2006; Friedler and Hadari, 2006).

Results also show that operational costs for the small-scale MBR were around 20 times higher than for large-scale MBRs with post-treatment. This is due to the operational inefficiencies inherent in small-scale plants and the subsequent staff time required maintaining and operating the system. Staffing accounted for 51% of operational costs while energy consumption accounts for 27%. This compares with large-scale plants, where the economies-of-scale reduces the operational and energy costs. The findings also show that to reduce the operational costs of small-scale MBRs (less than an equivalent of 100 households), the main focus of design should be on reducing manual maintenance by increasing operational efficiencies. In addition, post-treatment required to remove discolouration of water accounted for 29% of OPEX. If coloured water is acceptable for non-potable domestic applications, this could provide significant OPEX and CAPEX savings (Verrecht et al., 2012).

Water saving devices provided the most significant contribution in reducing on-site water consumption, reducing water consumption to almost 40% lower than locally metered properties. In addition, reclaimed water accounted for 15-20% of total water consumption. Overall, it resulted in mains water consumption being almost 50% lower than locally metered properties. Although, reducing water consumption below the 80 lpd threshold (required for Level 6 in the Code for Sustainable Homes) comes at a greater marginal cost through wastewater reclamation and reuse than through water saving devices. It is also revealed that in peri-urban environments such as BedZED - where the cost of land is lower than in dense urban environments – rainwater harvesting systems with large storage systems to attenuate seasonal rainfall patterns may present a more rational method for non-potable water supply than wastewater reclamation.

7. Discussion

Public perception is widely viewed as one of the main barriers to the implementation of water reuse schemes (Dolnicar and Hurlimann, 2010; Aitken et al., 2014). Whilst the current water exploitation approaches appears to be unsustainable, methods to develop change require a shift in social attitude towards water consumption by recognising the economic and environmental constraints. Public perception of water reuse may not improve until there are sufficient examples of successful schemes with adequate safety and security records.

Water reuse could provide environmental benefits by reducing demand for abstraction from natural water sources and the deposition of contaminants (Anderson, 2003). In order to value its contribution appropriately, further research is required to fully understand the positive and negatives environmental impacts that water reuse presents if implemented at a large scale.

The existing pilot schemes have shown that decentralised systems could perform more efficiently than traditional centralised in financial and economic terms, although they are currently far from achieving the efficiency of conventional systems. Economic feasibility is dependent on the scale of the scheme, treatment technology choice and the quality of wastewater and final treated water for reuse (Arpke and Clerico, 2006; Friedler and Hadari, 2006). Significant opportunities exist for these systems be optimised and to compete with conventional water supply from a cost perspective. In addition to technical efficiency gains, global examples of water reuse systems generally appear to be capable of meeting water quality criteria notably at levels above the legal requirements and public acceptability thresholds. Mainstreaming of water reuse practices could lead to refinement of standards, tolerances, and the quality requirements of reclaimed water in both potable and non-potable applications.

A transition towards the adoption of water reuse sources is likely to require the creation of financial incentives for the development and implementation of such networks. Without subsidy, the monopolistic nature of the market in which the majority of water utilities operate is not conducive to the creation of the 'niche markets' which support technological and systems innovation.

An adoption of decentralised water reuse networks may also hold implications for the performance of established wastewater networks by reducing sewer flow (Parkinson et al., 2005). Generally decentralised networks have been adopted on new build projects, which is less complicated than retrofitting the existing buildings and infrastructure. Further research is required into the difficulties and opportunities surrounding the integration of water reuse networks into the existing water and wastewater infrastructure.

Policy and regulation for water reuse is generally more established in areas with well-developed practices. The USA has national practice guidelines and individual states are responsible for the production of their own regulations. In contrast, the UK - which has far lower concentration of planned water reuse - has no specific guidelines or regulations, with projects applying US guidelines (Verrecht et al., 2012). The choice of the right blend of standards, reflecting the local requirements and characteristics, is critical as stringent requirements would restrict the implementation of water reuse projects and a further development of this field in the UK, whilst lenient regulation may encourage practices with unforeseen adverse outcomes. Further, the adoption of a publically visible standard with proven credentials can support the improvement of the public perception about water reuse.

As water utilities are generally public or regulated private bodies, government policies can dictates market behaviour. This can be directly seen in Japan where supporting policies directed the development of water reuse networks. Direct and indirect policies can be instated to respectively promote water reuse or alternative practices such as desalination and rainwater harvesting. Without effective policy, little incentive exists for the development of water reuse as its other drivers – such as environmental protection and hydrological capacity – are not financially recognised. Such policies and incentives should aim at creating the 'niche markets' required for the protection of novel technologies from conventional market forces (Geels, 2002).

As one of the first cities to adopt modern water and sewerage systems, London's aging infrastructure portfolio requires renewal. In addition, continued population growth in South-East England will extend the abstraction from natural water sources further towards or beyond their hydrological limits. In response to these constraints, an opportunity exists for a paradigm shift in water, sewer and storm provision which incorporates water reuse - in addition to other measures - to achieve a more environmentally and economically optimal system.

8. Conclusions

Water reuse provides opportunities to shift towards a more efficient and sustainable water supply system. Numerous infrastructural and technological arrangements exist, with the local governing constraints – including land availability, water markets, technological development, existing infrastructure, energy availability, public acceptability and freshwater availability – often determining which form of water reuse system is or should be implemented.

Aging infrastructure presents a bifurcation point where existing systems could be renewed or a new paradigm for water supply could emerge. Alternative supply methods, such as water reuse, provide an opportunity to augment existing water sources, a necessity driven by continued urban population growth, environmental degradation and economic constraint. Whilst alternative sources address the supply side of water management, a paradigm shift is likely to incorporate demand management methods such as smart metering and consumer behaviour change to further reduce strain upon hydrological constraints.

Public perception is commonly found to act as a significant barrier to the implementation of water reuse schemes. Public objection can be partially attributed to the lack of empirical evidence from existing schemes demonstrating system success and safety to public health. The lack of information may restrict the development of further schemes which are unable to progress upon past experiences. In addition, widespread variety in water reuse arrangements and applications demonstrates the requirement for local constraints to be appropriately represented when considering the costs and benefits of a new scheme. This is particularly a complex issue when integrating this new form of infrastructure within the existing ones.

Appropriate policies are also required for the development of novel decentralised water reuse technologies. Policy can trigger the creation of artificial niche markets which recognise the need to protect such emerging technologies and infrastructural arrangements from market forces. The establishment of appropriate water quality regulation could also encourage the emergence of water reuse technology and be subsequently slackened when systems have a proven tracked record and are publicly acceptable.

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List of Abbreviations

BedZED	Beddington Zero Energy Development
CDPH	California Department for Public Health
DPR	Direct Potable Reuse
EPA	Environmental Protection Agency
EU	European Union
GWTP	Green Water Treatment Plant
IPR	Indirect Potable Reuse
IUWM	Integrated Urban Water Management
Lpd	litres per day
MBR	Membrane bio-reactor
NPR	Non Potable Reuse
SCADA	Supervisory Control And Data Acquisition
SUDS	Sustainable Urban Drainage Systems
US	United States of America
WFD	Water Framework Directive
WHO	World Health Organisation

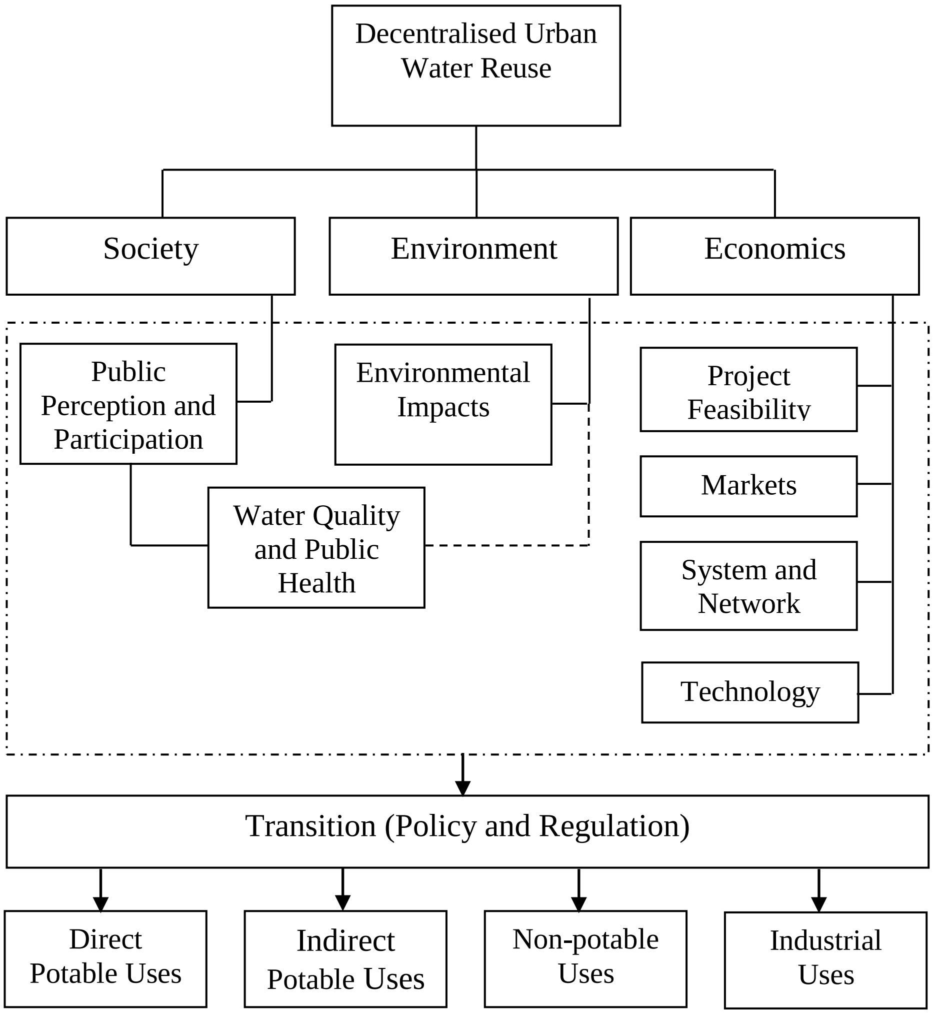

Figure 1 – A triple bottom line assessment framework for urban water reuse