

Design robustness of local water-recycling schemes

Evangelos Rozos¹, Christos Makropoulos² and David Butler¹

¹ *Centre of Water Systems, University of Exeter, Harrison Building, North Park Road, Exeter, EX4 4QF, UK*

² *School of Civil Engineering, National Technical University of Athens, Heroon Polytechniou 5, Athens, GR-157 80, Greece*

Tel.: +30 210 772 2886, Fax: +30 210 772 2832, cmakro@mail.ntua.gr

Abstract

The implementation of local water recycling and reuse practices is considered as a possible approach to managing issues of water scarcity. The sustainable design and implementation of a water recycle/reuse scheme has to achieve an optimum compromise between costs (including energy) and benefits (potable water demand reduction). Another factor that should be taken into account is the influence of potential changes in climatic conditions to the scheme's efficiency. These issues were assessed in this study using the Urban Water Optioneering Tool (UWOT). Two water-recycling schemes, a rainwater harvesting and a combination of rainwater harvesting and local greywater recycling, were assessed. The trade-off between potable water demand reduction, capital/operational cost and energy consumption of the two schemes was derived under three basic climatic conditions (Oceanic, Mediterranean and Desert) using evolutionary optimisation. Furthermore, the impact of changing climatic conditions on the suggested schemes was analysed to assess the robustness of the proposed design choices to climatic changes. The results indicate that schemes that are efficient in their use of local greywater are less susceptible to changes in climatic conditions, while schemes based exclusively on rainwater harvesting are more susceptible to changes, the more efficient they become.

Keywords: climate change, Koppen climate classification, multi-objective optimisation, NSGA-II, robustness, sustainable urban design, water recycling technologies

Introduction

Increasing water scarcity, caused by either climate change (Vorosmarty et al. 2000) or increasing consumption (Rosegrant et al. 2002) or both, has drawn attention to the

1
2
3
4 possibility of re-engineering the urban water cycle to implement water recycling and
5 reuse practices (Hurley et al. 2007; Liu et al. 2006; Makropoulos et al. 2006).

6
7 Examples of these new practices are the use of treated greywater (or “greenwater”)
8
9 for a variety of non-potable water uses in the household (Dixon et al. 1999; Leggett et
10 al. 2001; Memon et al. 2007; Shirley-Smith 2005) and at larger scales (see review by
11 Gikas and Tchobanoglous 2009). Experience suggests, however, that the successful
12 design and implementation of these new practices is not always straightforward
13
14 (Shirley-Smith and Butler 2008) and further support to practitioners is warranted,
15
16 including, but not restricted¹ to, the development of dependable, user-friendly tools
17
18 able to analyse/simulate the total water cycle.
19
20

21 The successful design of water recycling schemes should attempt to minimise at
22 the same time water, energy and cost, and perform adequately in the longer term –
23 possibly even under changing climatic conditions. In classic single-objective
24 approaches, these criteria are normalised and recombined into a single function using
25 weights. The main disadvantage of this approach is that the weights, i.e. the user
26 preferences, must be expressed prior to the optimisation run (Kapelan et al. 2003). To
27 avoid this disadvantage, a formal multi-criteria approach is preferable, able to produce
28 non-dominated solutions (in the form of a Pareto Front (PF)). This set of solutions can
29 be subsequently used as material for stakeholder consultation, assisting them to
30 visualise trade-offs between different criteria (Ningchuan et al. 2007) and to develop a
31 repository of alternative options from which a choice can be made after negotiation
32
33 (Srdjevic 2007).
34
35

36 This study developed sets of alternative design solutions for two water recycling
37 schemes under three basic climatic categories (Oceanic, Mediterranean and Desert),
38 using a decision support tool that simulates the total urban water cycle. The basic
39 structure and functionality of this tool, the Urban Water Optioneering Tool (UWOT),
40 is presented in Makropoulos et al. (2008).
41
42

43 In this study, UWOT was first applied as an optimisation tool. For this purpose the
44 multi-objective optimisation algorithm NSGA-II (Deb et al. 2000) was used to obtain
45 the PF of the “optimal” design variables for each of the two recycling schemes for a
46 range of criteria, under the three climatic conditions. UWOT was then used as an
47
48
49

50
51
52
53
54
55
56
57
58
59 ¹ Clearly there are more barriers to the implementation of novel water practices than analytical and
60 modelling tools’ availability. For a review of relevant work see for example Brown, R., Farrelly, M.
61 and K. Nina (2009).
62
63
64
65

1
2
3
4 assessment tool. The optimisation results from the Mediterranean climatic conditions
5 were assessed under a potential reduction of the annual precipitation providing an
6 estimate of the influence of changes in climatic conditions on the PF solutions.
7
8

9 The paper begins with a brief introduction to UWOT, including upgrades and
10 changes beyond those discussed in Makropoulos et al. (2008). The description of the
11 case study and the results of UWOT application is then presented and critically
12 discussed.
13
14
15

16 17 18 **Description of UWOT**

19 UWOT is a decision support tool that simulates the urban water cycle by modelling
20 individual water uses and technologies for managing them and assessing their
21 combined effects at development scale. UWOT simulates both “standard” urban water
22 flows (potable water, wastewater and runoff) as well as their integration through
23 recycling schemes (including for example greywater, treated greywater and
24 rainwater). The water system components of the development are represented inside
25 UWOT using a three level hierarchical structure (Figure 1):
26
27
28
29
30

- 31 1. **Lower level.** This level includes the individual household water appliances (e.g.
32 toilets, washing machines, local treatment units).
33
- 34 2. **Middle level.** This level includes the households as well as “central” technologies
35 (i.e. technologies such as centralised greywater treatment, centralised wastewater
36 treatment or a development scale drainage system). Each household includes (a)
37 water using appliances, (b) in-house water infrastructure (greenwater tanks,
38 pipeworks) and (c) a set of characteristics that affect the water budget (occupancy,
39 pervious/impervious area).
40
41
42
43
44
- 45 3. **Higher level.** The higher level is the urban development as a whole. An urban
46 development could range from a new neighbourhood to a new village or small
47 town. An urban development is defined by the number of household types
48 included in the development, the public pervious/impervious areas of the
49 development and the type of the recycling/treatment scheme.
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

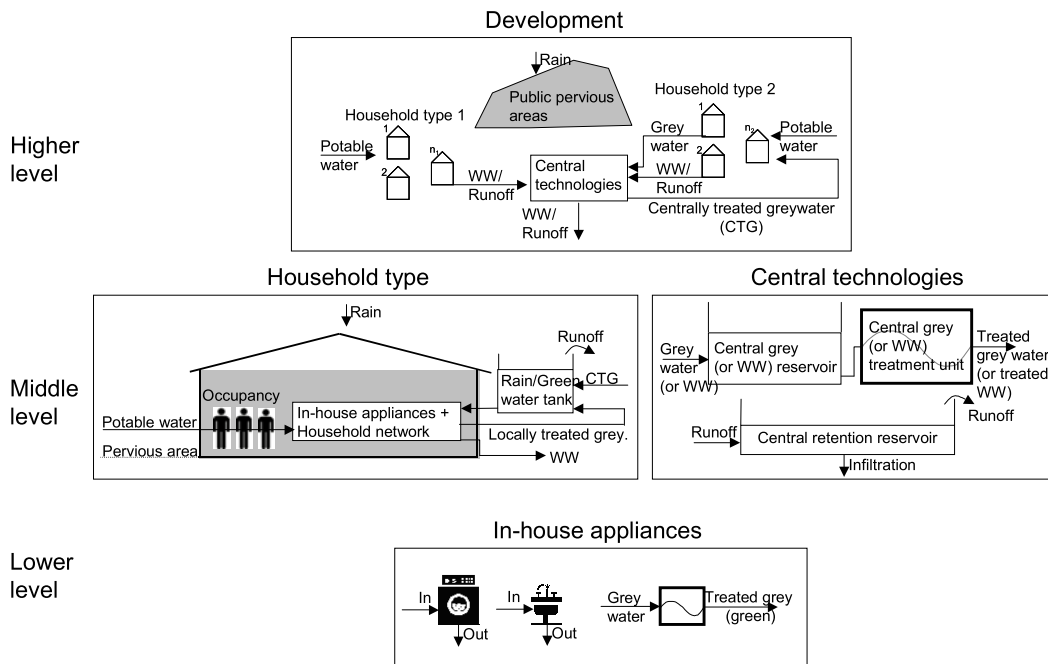


Figure 1: Hierarchical representation of the water system of an urban development in UWOT.

UWOT is linked to a database (hereafter referred to as the “technology library” (Sakellari et al. 2005) that contains information on the major characteristics of both in-house and development scale water system components. The type of information contained in the technology library for each technology is the following:

- **Local appliances.** The technology library contains operational characteristics that are necessary for the calculation of the water balance of the urban water cycle (e.g. water use per flush for a specific type of toilet and frequency of use). The library also contains the technical characteristics that influence the development of a series of indicators (e.g. required energy, cost). The information on local appliances that is included in the technology library was obtained from market surveys (including technical specifications provided by manufacturers (e.g. Pontos 2008)) as well as from research and practitioner manuals (e.g. the frequency of use and the water consumption per use for each appliance from Marshallsay et al. (2007)).
- **Central technologies.** The technology library contains the operational and technical characteristics of the technologies operating at the development scale.

1
2
3
4 These technologies differ from the local appliances in the sense that (a) they are
5 large units constructed on site; (b) their specifications are not predefined by
6 industrial standards but are tailored to the requirements of each development. For
7 these technologies the library contains relationships that relate the operational and
8 technical characteristics with their capacity. These relationships were obtained
9 from the studies of Joksimovic (2006) and Sostar-Turk et al. (2005).

- 14 • **Local tanks and central reservoirs.** The cost of local water tanks (used for
15 storing treated and untreated recycled water and rainwater) and central reservoirs
16 was assumed proportional to their volume.
- 17 • **Household piping.** The cost of household pipework required for water recycling
18 is assumed proportional to the household size. This lumped approach reduces the
19 number of required data by relating the pipework cost to a property of the
20 household. The proportionality coefficient was derived from pipework costs
21 discussed in March et al. (2004).

29 **Optimisation algorithm**

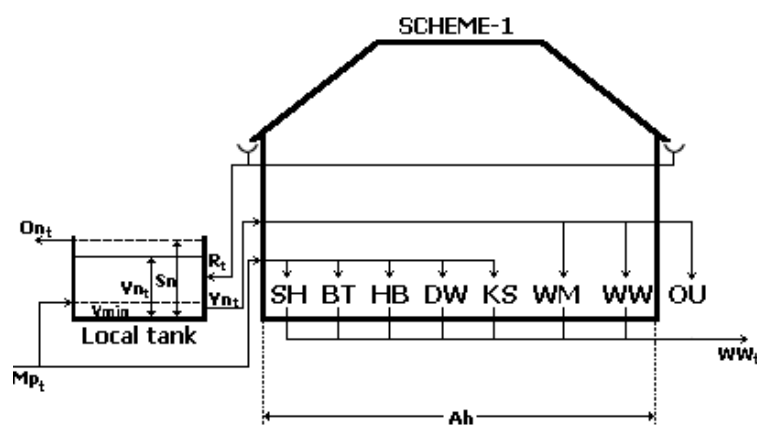
30 UWOT provides an assessment of modelled water system configurations using
31 quantitative and qualitative sustainability indicators (Ashley et al. 2008). A multi-
32 objective optimisation algorithm was linked with the current UWOT version using the
33 Excel add-in GANetXL (Bicik et al. 2004). GANetXL is written in C++ and exploits
34 a COM interface to interact with Excel. A user-friendly interface allows users to
35 configure the tool easily and to perform optimisations.

36 GANetXL is based on the non-dominated sorting multi-objective evolutionary
37 algorithm NSGA-II (Deb et al. 2000). The basic advantages of this algorithm is (a) the
38 reduced computational complexity (the complexity is $O(mN^2)$ compared to the usual
39 of $O(mN^3)$ where m is the number of objectives and N is the population size), (b) the
40 non-dominated sorting approach and (c) the use of a selection operator which creates
41 a mating pool by combining the parent and child populations and selecting the best
42 (with respect to fitness and spread) N solutions.

55 **UWOT Application**

56 In this paper two hypothetical water saving schemes employing local recycling and
57 water reuse techniques were studied:
58
59
60
61
62
63
64
65

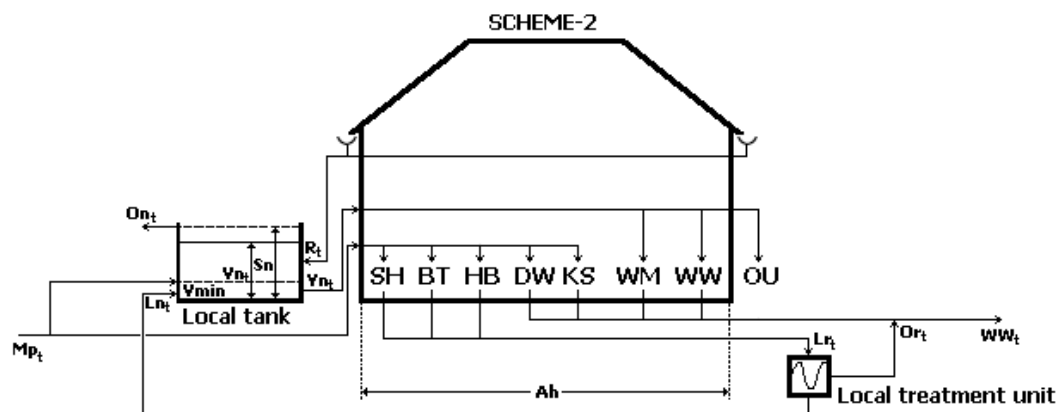
1
2
3
4 The first scheme is depicted in Figure 2. In this scheme the harvested
5 rainwater (R_t is the harvested rainfall volume during the time interval t from the
6 rainwater harvesting area A_h) is stored in a local tank and used for toilet flushing,
7 washing machine and outside uses (Y_{nt} is the water yield volume from local tank
8 during the time interval t). This should be considered realistic as work has shown that
9 use of rainwater within the household does not generally have adverse (health or
10 technical) effects (e.g. for use of rainwater in washing machines see Herrmann and
11 Schmida (2000)). Clearly local characteristics of the rain and of the roofs or collecting
12 areas need to be taken into account, but health impact assessment studies have shown
13 rainwater harvesting to be a low risk water source (Heyworth et al. 2006; Fewtrell and
14 Kay 2008). The rest of the appliances are supplied with potable water from water
15 mains (M_{pt} is the potable water volume supplied from the mains to the household
16 during the time interval t). Potable water from the mains is also used to ensure that the
17 water level (V_{nt} is the water volume in store at the beginning of the time interval t)
18 in the local tank does not drop under a minimum threshold (V_{min}). If the water level
19 exceeds the local tank capacity (S_n) the surplus water is spilled (O_{nt} is the overflow
20 volume from the local tank during the time interval t) into the rainwater drainage
21 system. The output of all local appliances is considered wastewater and is sent to the
22 wastewater drain (WW_t is the wastewater volume produced from the household
23 during the time interval t).



58 **Figure 2:** Schematic representation of water saving scheme-1. SH for shower, BT for bath, HB for
59 hand basin, DW for dish washer, KS for kitchen sink, WM for washing machine, WW for toilet and
60 OU for outside uses

1
2
3
4 The second scheme is depicted in Figure 3. The difference from the previous
5 scheme is that greywater from the shower, bath and hand basin (Lr_t is the greywater
6 volume from the household appliances during the time interval t) is treated locally and
7 stored in a local tank (Ln_t is the treated greywater volume from the local greywater
8 treatment unit during the time interval t) along with the harvested rainwater. Organic
9 sediments and particles are filtered out in the local greywater treatment unit and
10 diverted into the wastewater drain (Or_t is the volume of the excess greywater plus
11 water losses and by-products from greywater treatment during time the interval t).
12 The water losses and flow of by-products was assumed here (conservatively) to be 3%
13 of the incoming flow, as an example. This value is a function of the efficiency of the
14 particular treatment technology used and can be specified by the user through
15 UWOT's technology library.
16
17
18
19
20
21
22
23

24 The treatment process included in this specific scenario comprises of four
25 treatment stages: Initially the incoming greywater is filtered and then two stages of
26 bio-mechanical cleaning process follow. Finally the water is sterilized using UV. It is
27 suggested that this level of treatment is feasible and given the sources of greywater in
28 our scenario, and its eventual mix with rainwater, the resulting water quality should
29 be quite adequate for the investigated uses (toilet flushing, washing machine and
30 outside uses).
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52



53 **Figure 3:** Schematic representation of water saving scheme-2.
54

55 To increase optimisation speed and simplify the modelling exercise, a test
56 development with only one household is investigated in this study (an unrestricted,
57 user-defined number of houses can be simulated by UWOT, with household results
58 aggregated at the development scale). This household was assumed to have 130 m² of
59
60
61
62
63
64
65

1
2
3
4 rainwater harvesting area and 4 occupants (i.e. the typical 4 bedrooms household of
5 the Elvetham Heath development in the UK (Parsons and Sim 2007)).
6

7 The simulation time step was daily (see Makropoulos et al. (2009) for a discussion
8 on the effect of daily time steps on realistic representations of the urban water cycle)
9 and the simulation period length was five years (five years with daily time step is the
10 maximum number of simulation time steps allowed by the current model version).
11 The two schemes were examined using three time series of daily rainfall obtained
12 from the Freemeteeo² database. The first time series is recorded from a meteorological
13 station in London Heathrow Airport, the second from a meteorological station in
14 Paphos Airport in Cyprus and the third from a meteorological station in Qatar's Doha
15 Airport. All time series start at 1 October 2000 and end at 30 September 2005. The
16 average monthly rainfall and the average rainfall events per month at these locations
17 (for this specific 5-year period) are displayed in Figure 4 (Vose et al. 1992). The
18 corresponding annual precipitations at Heathrow, Paphos and Doha airports are
19 671.34 mm, 433.8 mm and 61.5 mm respectively.
20
21
22
23
24
25
26
27
28
29

30 These locations according to the Koppen classification (Peel et al. 2007) belong to
31 the climatic categories Cfb (Oceanic climate), Csa (Mediterranean climate) and BWh
32 (Desert) respectively. In this study the results from each one of these three timeseries
33 are used to derive general conclusions for the corresponding climatic category.
34
35

36 The water demand is calculated by UWOT using the frequency of use and the
37 required amount of water per use of each household appliance. These are considered
38 constant during the simulation period and unaffected by the climate to facilitate
39 comparisons. This is, of course, a simplification, particularly as far as outdoor uses
40 are concerned, since in dryer climates evapotranspiration is expected to increase and
41 hence one could argue for increased outdoor uses. However not every outdoor use is
42 affected by the climatic conditions (for example, car washing). Furthermore it is less
43 than straightforward to determine how increased evapotranspiration will affect water
44 consumption for outdoor uses: In dryer climates, for example, increased irrigation
45 needs for the same area and the same vegetation are expected and can be calculated.
46 Nevertheless, adaptation practices involving smaller vegetation areas and different
47 types of plants cannot be ignored, leaving irrigation needs potentially unaffected
48 (Balling et al. 2008). It is therefore suggested that the simplifying approach adopted in
49
50
51
52
53
54
55
56
57
58
59

60
61 ² freemeteeo.com (Retrieved at 25 October 2008)
62
63
64
65

these simulations, treating uses as constant with climatic changes, is justified by the lack of more a specific socio-cultural evidence base.

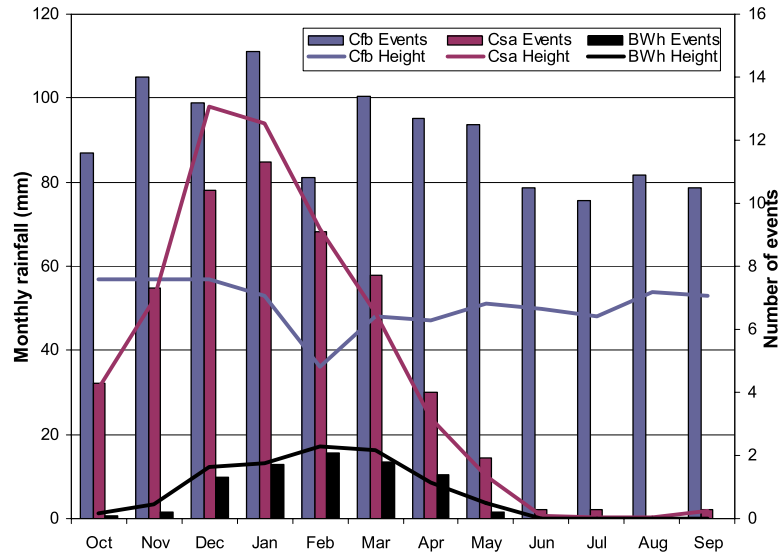


Figure 4: Monthly rainfall characteristics of Cfb, Csa and BWh climatic conditions. Cfb, Csa, BWh Events: the average number of rainfall events per month in the Cfb, Csa, BWh climatic conditions. Cfb, Csa, BWh Height: the average monthly rainfall depth per month in the Cfb, Csa, BWh climatic conditions.

The study for each of the two schemes was conducted in two stages:

During the *first stage*, the characteristics of each of the two schemes were optimised using the GANetXL optimisation algorithm. The parameters to optimise and the optimisation constraints are displayed in Table 1. The local treatment unit with id 1 corresponds to a unit with a capacity of 150 l/d whereas the local treatment unit with id 3 corresponds to a unit with a capacity of 600 l/d. The four objectives used for optimisation were: potable water demand, capital cost, operational energy (required for the greywater treatment process, sterilization and pumping of the treated greywater back to the rain/green water tank) and operational cost (maintenance cost i.e. labour and spare parts cost). The NSGA-II algorithm parameters are displayed in Table 2.

Table 1: Optimised water system components in each scheme along with the optimisation constraints.

	Household local tanks (l)		Household local treatment unit id	
	min	Max	min	max
Scheme-1	0	12000	-	-
Scheme-2	0	12000	1	3

1
2
3
4
5
6 **Table 2: NSGA-II algorithm parameters**

Population	70
Crossover rate	0.95
Mutation rate	0.05
Number of generations	1000

11
12
13 During the *second stage*, the influence of a potential change of prevailing climatic
14 conditions on the two test schemes was investigated. The design resulting from the
15 multi-objective optimisation under Csa climatic conditions was examined under a
16 potential reduction of the annual precipitation to assess its robustness.
17

18
19 It should be noted that the parameters included in Table 1 are not the only
20 parameters that could be optimised using UWOT. Additional parameters could
21 include:
22

- 23 ○ type of water appliances used in the household (in each of the six household
24 “types” UWOT supports).
- 25 ○ percentage of impervious/pervious/rainwater-harvesting areas
- 26 ○ type of water recycling scheme (at the household or development scale)

27
28 More information on UWOT parameters, which can all be subject to optimisation, can
29 be found in Makropoulos et al (2008). Clearly, requesting additional parameters to be
30 optimised would have an impact on optimisation time.
31
32

33 **Results**

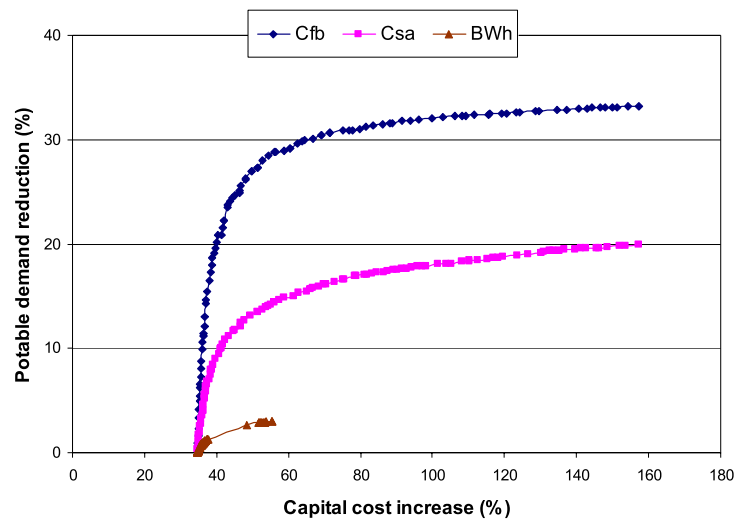
34 *A. Stage 1: Pareto Front (PF) of scheme-1 and scheme-2*

35 The parameter to be optimised in scheme-1 (tank capacity) influences only two out of
36 the four objective functions (specifically capital cost and potable water demand since
37 greenwater is assumed to be supplied by gravity eliminating any requirements for
38 energy and operational cost). The trade-off between capital cost and potable water
39 demand reduction for scheme-1 for Cfb, Csa and BWh climatic conditions is
40 displayed in Figure 5. The percentage increase of the capital cost is calculated with
41 respect to the capital cost of a conventional water system (no water recycling/reuse).
42 All curves in Figure 5 intersect the x-axis at 34%. This reflects capital cost increase
43 due to the installation of the pipework (which is common to all solutions).
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4 A capital cost increase of 64% in Cfb (Oceanic) climatic conditions results in a
5 reduction of potable water demand by 30%. Only marginal further reduction can be
6 achieved even with significant capital cost increase.
7
8

9 In Csa (Mediterranean) climatic conditions a capital cost increase of 64% results
10 in only 15% potable demand reduction. The maximum achievable potable water
11 demand reduction is 20%, which can be achieved with increasing capital cost by
12 160%.
13
14

15 The maximum achievable potable demand reduction in BWh (Desert) climatic
16 conditions is less than 3%. This reduction can be achieved with a 55% increase in
17 capital cost.
18
19
20



21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39 **Figure 5:** Potable water demand reduction (%) versus capital cost increase (%) of scheme-1 under Cfb,
40 Csa and BWh climatic conditions.
41

42
43 Parallel Coordinate Plots (PCPs) (Inselberg and Dimsdale 1990; Ward 1994) were
44 used to visualise the results of multi-objective optimisation for scheme-2. In PCPs
45 each objective function is plotted against a different axis. The N axes (in this case the
46 4 axes) are organised as uniformly spaced vertical lines. Each solution of the N-
47 dimensional (in this case 4D) PF manifests itself as a set of points, one on each axis.
48 To improve graph clarity, only the boundaries and the median of the set of points in
49 each axis are presented (see Figure 6 and Figure 7).
50
51

52 In the present case study the four objective function values differed by orders of
53 magnitude and for this reason standardised values were used in the PCPs. The
54 objective function values were standardised using the formula $(O_{ij} - \mu_j) / \sigma_j$ where: O_{ij} is
55 the j^{th} objective-function value (j ranges from 1 to 4 where 4 is the number of the
56
57
58
59
60
61
62
63
64
65

objective functions) for the i^{th} PF solution (i ranges from 1 to 70 where 70 is the population size), μ_j is the average of the O_{ij} for $i=1, \dots, 70$ and σ_j is the standard deviation of the O_{ij} for $i=1, \dots, 70$.

The results of the optimisation of scheme-2 are displayed in Figure 7. From this figure the following can be noted for scheme-2:

- The median values of energy and operational cost under Cfb climatic conditions are very close to (almost coincide with) the lower boundaries.
- The higher median value of capital cost occurs under Csa climatic conditions.
- The median values of energy and operational cost under BWh climatic conditions are closer to the upper boundaries.

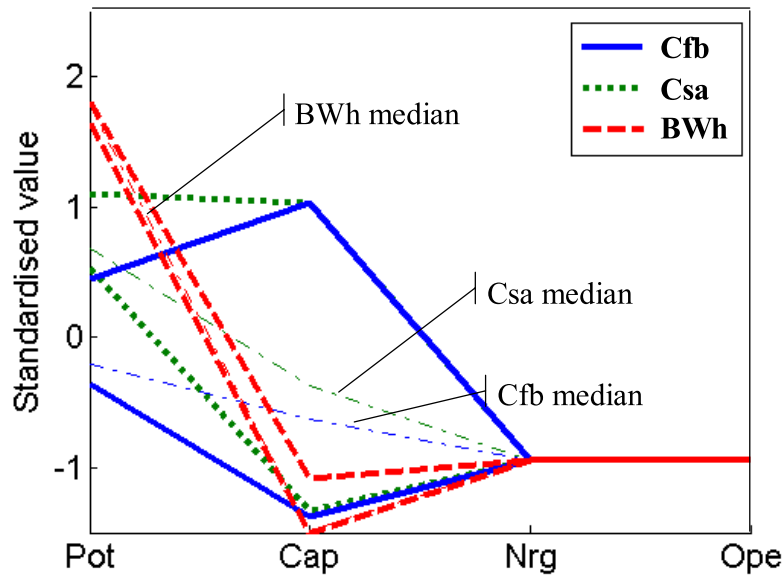


Figure 6: PCP of scheme-1 for Cfb, Csa and BWh climatic conditions. In the vertical axis the standardised values of the objective functions. Pot: the potable water demand; Cap: the capital cost; Nrg: the operational energy; Ope: the operational cost.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

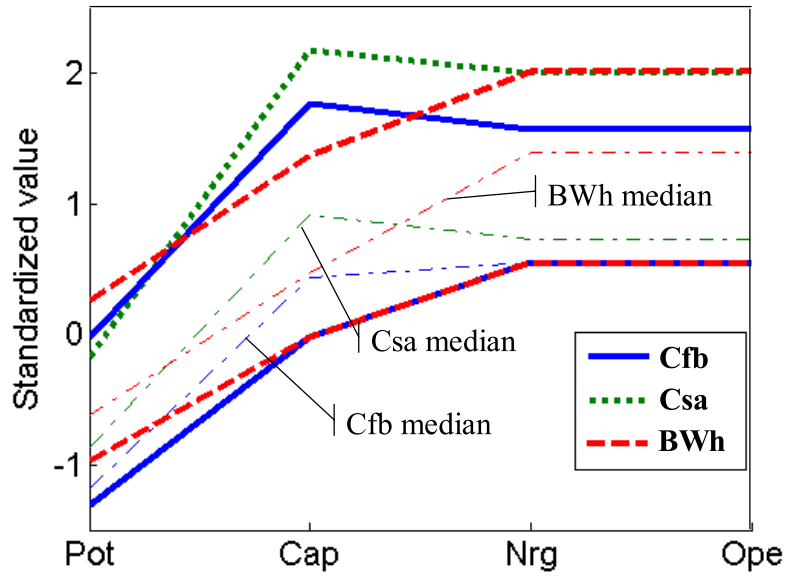


Figure 7: PCP of scheme-2 for Cfb, Csa and BWh climatic conditions. In the vertical axis the standardised values of the objective functions. Pot: the potable water demand; Cap: the capital cost; Nrg: the operational energy; Ope: the operational cost.

The consumption per water type of scheme-1 PF solutions that achieved the minimum potable water demand (regardless of the cost) under Cfb, Csa and BWh climatic conditions is displayed in Figure 8. This figure indicates that scheme-1 achieved negligible water saving in BWh climatic conditions.

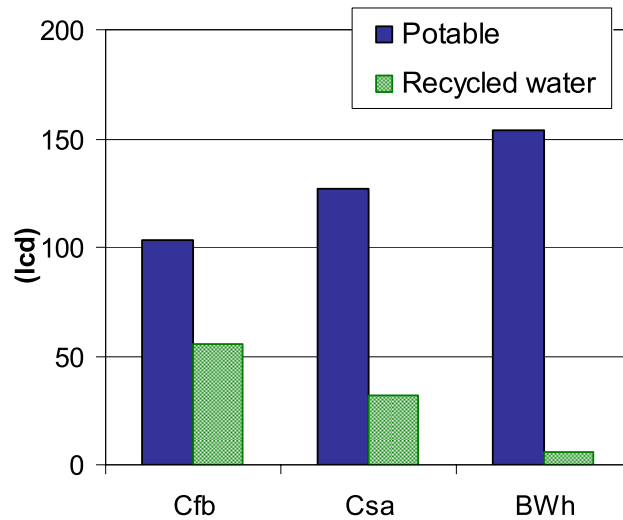


Figure 8: Consumption per water type of the scheme-1 PF solutions that achieved the minimum potable water demand under Cfb, Csa and BWh climatic conditions.

1
2
3
4 The consumption per water type of scheme-2 PF solutions that achieved the
5 minimum potable water demand (regardless of the costs and energy) under Cfb, Csa
6 and BWh climatic conditions is displayed in Figure 9. This figure suggests that
7 scheme-2 achieved satisfactory water savings even in BWh climatic conditions.
8
9 Recycled water (including both treated greywater and harvested rainwater) covers
10 47%, 47% and 42% of the water demand in Cfb, Csa and BWh climatic conditions
11 respectively.
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

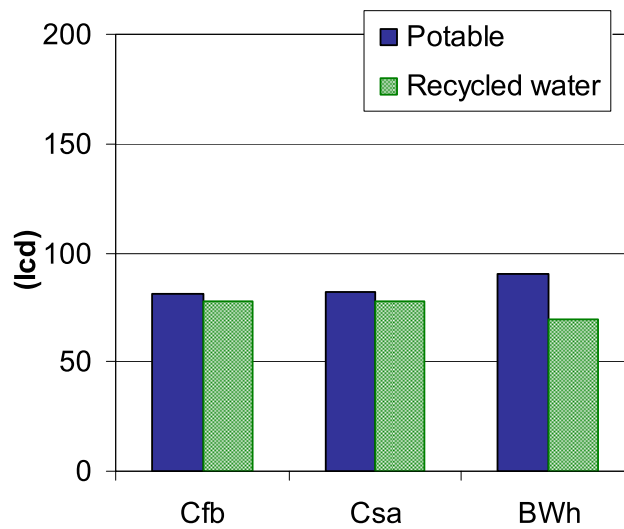
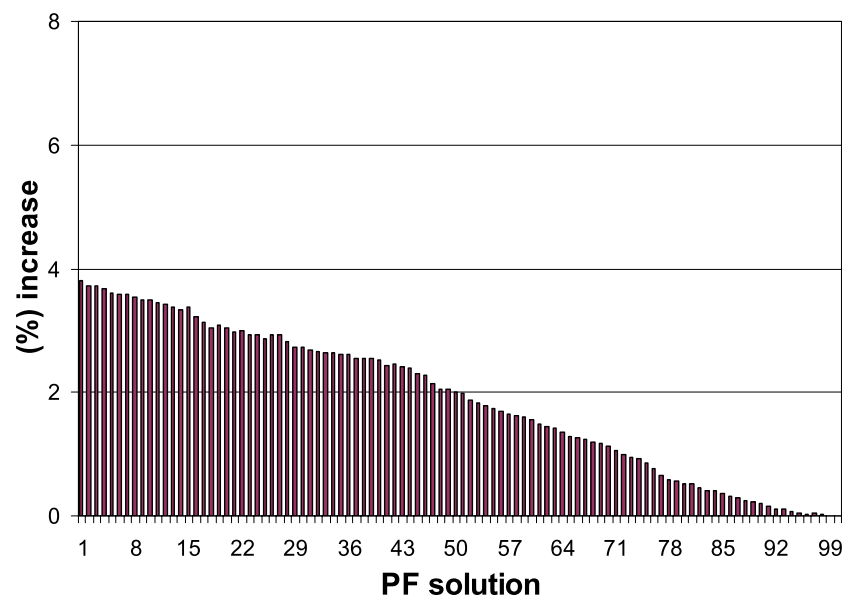


Figure 9: Consumption per water type of the scheme-2 PF solutions that achieved the minimum potable water demand under Cfb, Csa and BWh climatic conditions.

1
2
3
4 *B. Stage 2: Impact of changes in climatic conditions*

5 According to recent reports of the Intergovernmental Panel on Climate Change (IPCC
6 2007) the trend of annual precipitation is positive in regions with Cfb climatic
7 conditions. On the other hand, annual precipitation is expected to decrease by 20% by
8 the end of 21st century in many regions currently characterised by Csa climatic
9 conditions. For this reason the 70 PF solutions of the two schemes for Csa climatic
10 conditions were assessed using the historical rainfall time series multiplied by a
11 reduction coefficient equal to 0.8. Figure 10 presents the percent increase of potable
12 water demand of the 70 scheme-1 solutions assessed under rainfall time series with
13 reduced annual precipitation. The maximum increase of demand for potable water (as
14 opposed to recycled) is almost 4%.
15
16
17
18
19
20
21
22
23
24
25



48 **Figure 10:** Percentage increase of the potable water demand of the scheme-1 PF solutions for Csa,
49 assessed under reduction of annual precipitation by 20%.

50
51
52
53
54 The percentage increases of demand for potable water of the 70 scheme-2
55 solutions are shown in Figure 11. The maximum percentage increase is almost 1.5%.
56
57
58
59
60
61
62
63
64
65

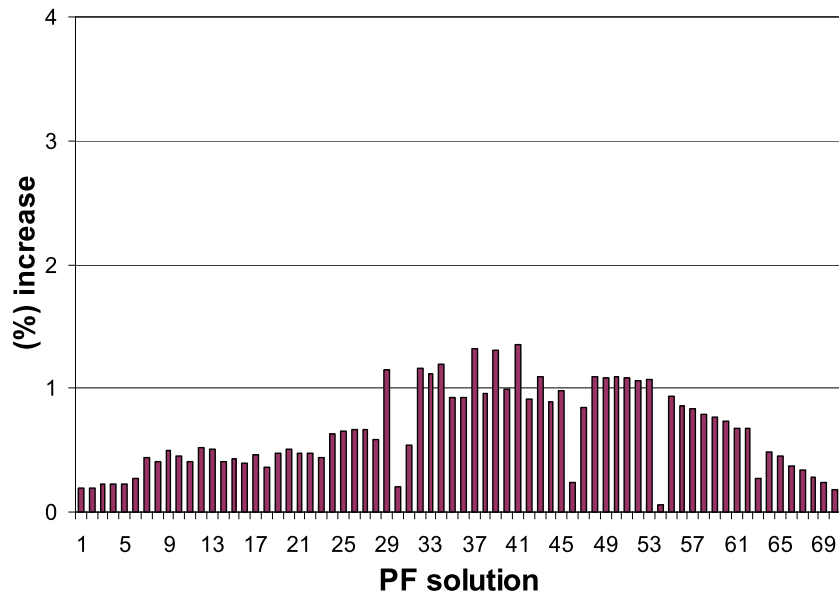


Figure 11: Percentage increase of the potable water demand of the scheme-2 PF solutions for Csa, assessed under reduction of annual precipitation by 20%.

Discussion

A. Scheme-1

The maximum rainwater that can be harvested (given by the rainwater harvesting area multiplied by the annual rainfall depth) in Cfb, Csa and BWh climatic conditions is 87.3, 56.4 and 8.0 m³/year or 240, 155 and 22 l/d respectively. This is equal to the 37%, 24% and 3% of the household water demand. The corresponding estimated values from UWOT, indicating solutions that achieved the greater potable water demand reduction, are 226, 130 and 23 l/d (Figure 8) or 35%, 20% and 3% of the water demand. These values are slightly lower than the values corresponding to the maximum rainwater that can be harvested because of the optimisation constraints (see local tanks max size in Table 1).

The dependence of the performance of the scheme on climatic conditions is indicated in Figure 6. A close look in the Cfb PCP-plots in Figure 6 and Figure 7 reveals that the potable water demand median of scheme-1 is inside the scheme-2 boundaries. This means that under Cfb climatic conditions, some of the scheme-1 solutions achieved the same potable water demand reduction as some of the scheme-2

1
2
3
4 solutions. This does not happen in the other two climatic conditions meaning that in
5
6 Csa and BWh climatic conditions, all solutions of scheme-1 achieved less potable
7
8 water demand reduction than any of the scheme-2 solutions. In BWh climatic
9
10 conditions the boundaries are very close to each other (Figure 6) indicating the lack of
11
12 efficient alternative solutions.

13
14 The increase of potable water demand due to a reduction in the annual
15
16 precipitation (climate change) can be estimated by multiplying the present potable
17
18 water demand with the coefficient r_{AB} where:

$$r_{AB} = \frac{D_{\text{tot}} - \min(R_B, D_{\text{grn}})}{D_{\text{tot}} - \min(R_A, D_{\text{grn}})} \quad (1)$$

19
20 where: D_{tot} the daily water demand [L^3], D_{grn} the daily green water demand [L^3], R_A
21
22 the average daily harvested rainfall of the present climatic conditions [L^3], R_B the
23
24 average daily harvested rainfall of the future climatic conditions [L^3].
25
26

27
28 The potable water demand increase, when assessing the Csa PF solutions under
29
30 reduction of the annual precipitation by 20%, is according to (1) 6.3%. This value
31
32 corresponds to the theoretical case where the annual rainwater harvesting capacity
33
34 equals to the annual precipitation. A comparison with the maximum value of Figure
35
36 10 suggests that equation (1) can be used to obtain an estimation of the effect of
37
38 climate change on a recycling scheme that is based exclusively on rainwater
39
40 harvesting.

41
42 The potable water demand increase is lower for the solutions on the right side of
43
44 the bar plot in Figure 10. The solutions on the right side are the low cost
45
46 implementations with small tank capacities. In other words this figure suggests that
47
48 the more efficient a rainwater harvesting scheme is, the more susceptible it is to
49
50 changes in climatic conditions.

51 *B. Scheme-2*

52
53 In Cfb climatic conditions, the average number of rainfall events per month varies
54
55 between 10 and 15 (Figure 4) and the average monthly rainfall depth between 36 and
56
57 57 mm. This relatively uniform distribution of rainfall-events' frequencies and rainfall
58
59 depths throughout the hydrological year, results in a sufficient amount of harvested
60
61 rainwater. Only a limited extra supply from the local greywater treatment unit is
62
63 required to cover the household demand for recycled water. This limited supply can
64
65

1
2
3
4 be provided with low operational cost and energy consumption. This explains the
5 proximity of the median values of energy and operational cost to the lower boundaries
6 in Figure 7.
7
8

9 The PF solutions of Csa climatic conditions tend to require a larger capital cost
10 than the solutions of the other two climatic conditions because they suggest larger
11 tanks are needed. The tanks in Csa tend to be larger than the other climatic conditions
12 to take advantage of the considerable annual precipitation depth that is however
13 characterised by a significant variation of events frequency during the hydrological
14 year (Figure 4, the average number of events per month varies between 0 and 11).
15
16

17 The PF solutions of BWh climatic conditions tend to use small tanks because of
18 the very low annual precipitation. To compensate for the reduced annual precipitation,
19 the BWh PF solutions tend to use larger local treatment units than the other climatic
20 conditions. This explains why the median values of energy and operational cost are
21 higher than those of the other climatic conditions in Figure 7.
22
23

24 In this case study, the demand from appliances that are supplied from the local
25 tank using recycled water (washing machine, toilet and outside uses) was 306 l/d or
26 47% of the total household water demand (the demand of the remaining appliances,
27 supplied with potable water, is 347 l/d). Figure 9 indicates that the appropriate
28 solution can efficiently reduce the potable water demand even in BWh climatic
29 conditions. The Cfb and Csa solutions of Figure 9 supply enough recycled greywater
30 to fully cover the demand of the appliances that can use it. The BWh solution covers
31 with recycled greywater 90% of the demand of the appliances that can use it (the
32 remaining 10% is covered with potable water).
33
34

35 Figure 11 indicates that the scheme is hardly influenced by changes in climatic
36 conditions.
37
38
39
40
41
42

43 44 45 46 47 48 49 50 **Conclusions**

51 Two water recycling schemes ((a) rainwater harvesting only and (b) rainwater
52 harvesting plus local greywater treatment) were optimised for three climatic
53 conditions (Cfb, Csa and BWh) using the UWOT decision support tool. A multi-
54 objective optimisation approach was used to obtain a set of alternative solutions
55 (Pareto front) for each climatic condition. The Pareto front solutions of the Csa
56
57
58
59
60
61
62
63
64
65

1
2
3
4 climate were then examined under reduced annual rainfall by 20%, following IPCC
5 recommendations. The results of this investigation can be summarised as follows:
6

- 7 1. A local rainwater harvesting scheme can only offer minor potable water demand
8 reduction (3%) under BWh climatic conditions. The same scheme can provide a
9 reduction to potable water demand by 20% in Csa climatic conditions but with a
10 significant increase in capital cost (of the order of 160%). In Cfb climatic
11 conditions a 30% reduction of demand for potable water can be achieved with an
12 increase of capital cost by 64%. Assuming annual interest equal to 3% (average
13 rate of interest on investment account for the period 2001-2007, UK Office of
14 National Statistics 2009) and water price 1.6 £/m³ (South West Water 2009) the
15 payback period for this capital cost increase would be 25 years (the corresponding
16 period, for capital cost increased by 64%, would be 40 years in Csa climatic
17 conditions).
18
19 2. The combination of rainwater harvesting with a local greywater treatment unit can
20 reduce the demand for potable water by more than 42% even in BWh climatic
21 conditions. Furthermore, this scheme is hardly influenced by changes in climatic
22 conditions. The disadvantage of this scheme is that both operational cost and
23 required energy increase in climates with low annual precipitation. This is
24 consistent with the trade-off identified between water and energy in urban water
25 management for a given technological level (Butler and Makropoulos 2006).
26
27
28
29
30
31
32
33
34
35
36
37
38
39

40 Ultimately, the paper articulates and quantitatively supports an intuitive conclusion:
41 Although rainwater harvesting alone (if properly designed), can achieve significant
42 reductions in the demand of potable water for in-house uses, in a range of different
43 climates, this water sources depends on stochastic phenomena (climatic conditions,
44 including rainfall and temperature) whose variation introduces long term uncertainties
45 in the systems' performance. To the extent these variations are significant, this
46 uncertainty can be counter-balanced by introducing a level of system redundancy, in
47 the form of capturing, treating and recycling greywater as well. Although this
48 improves the robustness of the overall solution under changing conditions, due to the
49 invariant nature of greywater as a water resource, this is by no means a no-cost
50 option. It results in an increase of maintenance and energy costs, the extent and
51 availability of which is linked to technological innovation and the renewable or
52 otherwise nature of energy resources.
53
54
55
56
57
58
59
60
61
62
63
64
65

References

- Ashley, R., Butler, D., Hurley, L. and Memon, F. (2008). Criteria and indicators in delivering sustainable water systems: from Sustainable Water Asset Resource Decisions (SWARD) to Water cycle management for New Developments (WaND), In DayWater: an Adaptive Decision Support System for Urban Stormwater Management, D. R. Thevenot (ed), IWA Publishing.
- Balling RC, Gober P, and Jones N (2008). Sensitivity of residential water consumption to variations in climate: An intraurban analysis of Phoenix, Arizona, *Water Resources Research*, 44, 10, W10401, doi:10.1029/2007WR006722.
- Bicik, J., Morley, M. S., Keedwell, E. C. and Savic, D. A. (2004). "GANetXL", <<http://www.centres.exeter.ac.uk/cws/ganetxl>> (March, 2008).
- Brown, R., Farrelly, M. and K. Nina (2009). Practitioner Perceptions of Social and Institutional Barriers to Advancing a Diverse Water Source Approach in Australia, *International Journal of Water Resources Development*, 25, 1, pp. 15-28
- Butler, D. and Makropoulos, C. (2006). Water Related Infrastructure for Sustainable Communities. Technological Options and Scenarios for Infrastructure Systems. Science Report SC05002501. Environment Agency. ISBN: 184432611X, available online: <<http://publications.environment-agency.gov.uk>>, (March, 2008).
- Deb, K., Agrawal, S., Pratap, A. and Meyarivan, T. (2000). A Fast Elitist Non-Dominated Sorting Genetic Algorithm for Multi-Objective Optimization: NSGA-II, Proceedings of the Parallel Problem Solving from Nature VI (PPSN-VI), Paris, France, 18-20 September 2000, pp. 849-858.
- Dixon, A.M., Butler, D. and Fewkes, A. (1999). Water Saving Potential of Domestic Water Reuse Systems Using Greywater and Rainwater in Combination, *Water Science and Technology* 39, 5, pp. 25-32.
- Fewtrell, L., Kay, D. (2008). Health Impact Assessment for Sustainable Water Management, IWA Publishing, Print ISBN: 9781843391333
- Gikas, P. and G. Tchobanoglous (2009). The role of satellite and decentralized strategies in water resources management, *Journal of Environmental Management*, 90, 1, pp. 144-152
- Herrmann, T., and Schmida, U. (2000). Rainwater utilisation in Germany: efficiency, dimensioning, hydraulic and environmental aspects, *Urban Water*, 1, 4, pp.307-316.
- Heyworth, J., G Glonek, EJ Maynard, PA Baghurst and J Finlay-Jones (2006). Consumption of untreated tank rainwater and gastroenteritis among young children in South Australia, *International Journal of Epidemiology* 35, 4, pp. 1051-1058

- 1
2
3
4 Hurley, L., Mounce, S.R., Ashley, R.M. and Makropoulos, C.K. (2007). Support for more
5 sustainable decision making in urban water management. CCWI07 Conference, Leicester,
6 UK, September 2007.
7
8
9 Inselberg, A. and Dimsdale, B. (1990). Parallel coordinates: a tool for visualizing
10 multidimensional geometry. Proceedings of the First IEEE Conference on Visualization, pp.
11 361-378.
12
13 Intergovernmental Panel on Climate Change (IPCC) (2007). Climate Change 2007: Synthesis
14 Report, Spain.
15
16 Joksimovic, D. (2006). Decision support system for planning of integrated water re-use
17 systems, Ph.D. thesis, University of Exeter, December 2006.
18
19 Kapelan, Z.S., Savic, D.A. and Walters, G.A. (2003). Multiobjective Sampling Design for
20 Water Distribution Model Calibration, J. Water Resour. Plng. and Mgmt. 129, 6, pp. 466-
21 479.
22
23 Leggett, D.J., Brown, R., Brewer, D., Stanfield, G. and Holliday, E. (2001). Rainwater and
24 greywater use in buildings: best practice guidance, CIRIA publication C539, London,
25 ISBN: 0860175397.
26
27
28 Liu, S., Makropoulos, C.K., Memon, F.A. and Butler, D. (2006). An object based household
29 water cycle model: concept and construction, Water Practice and Technology, IWA online
30 journal, 2, 2.
31
32
33 Makropoulos, C. K., Rozos, E. and Butler, D. (2009). Urban Water Modelling And The Daily
34 Time Step: Issues For A Realistic Representation, 7th ISE & 8th HIC, Concepción, Chile,
35 2009.
36
37
38 Makropoulos, C. K., Natsis, K., Liu, S., Mittas, K., and Butler, D. (2008). Decision Support
39 for Sustainable Option Selection in Integrated Urban Water Management, Environmental
40 Modelling and Software, 23, 12, pp. 1448-1460.
41
42
43 Makropoulos, C.K., Morley, M., Memon, F.A., Butler, D., Savic, D. and Ashley, R. (2006). A
44 Decision Support Framework for Sustainable Urban Water Planning and Management in
45 New Urban Areas, Water Science & Technology, 54, 6-7, pp. 451-458.
46
47
48 March, J.G, Gual, M. and Orozco F. (2004). Experiences on greywater re-use for toilet
49 flushing in a hotel (Mallorca Island, Spain), Desalination, 164, pp. 241-247.
50
51
52 Marshallsay, D., Trew, J. and Waylen C. (2007). Assessing the cost of compliance with the
53 code for sustainable homes, UK Environment Agency.
54
55
56 Memon, F.A. , Zheng, Z., Butler, D., Shirley-Smith, C., Liu, S. Makropoulos, C.K. and
57 Avery, L. (2007). Life cycle impact assessment of greywater treatment technologies for
58 new developments, Journal of Environmental Monitoring and Assessment, 129, 1-3, pp. 27-
59 35.
60
61
62
63
64
65

- 1
2
3
4 Ningchuan, X., Bennett, D.A. and Armstrong, M.P. (2007). Interactive evolutionary
5 approaches to multiobjective spatial decision making: A synthetic review, *Computers,*
6 *Environment and Urban Systems*, 31, 3, pp. 232-252.
- 7
8
9 Parsons, J. and Sim, P. (2007). WaND briefing note 25, Elvetham Heath Developer Survey.
- 10
11 Peel, M. C., Finlayson, B. L. and McMahon, T. A. (2007). Updated world map of the
12 Köppen-Geiger climate classification, *Hydrol. Earth Syst. Sci.*, 11, 5, pp. 1633-1644.
- 13
14 Pontos (2008). "Technical data AquaCycle 900", <[http://www.pontos-](http://www.pontos-aquacycle.com/pontos/en/)
15 [aquacycle.com/pontos/en/](http://www.pontos-aquacycle.com/pontos/en/)>, (Oct. 28, 2008).
- 16
17 Rosegrant, M.W., Cai, X. and Cline, S. (2002). *World Water and Food to 2025,*
18 *International Food Policy Institute, Washington, DC*, p. 5.
- 19
20 Sakellari, I., Makropoulos, C., Butler, D. and F. A. Memon (2005). Modelling sustainable
21 urban water management options. *Proceedings of ICE, Engineering Sustainability*, 158, 3,
22 pp 143-153.
- 23
24 Shirley-Smith, C. (2005). The sustainability value of the green roof water recycling system in
25 urban communities, WATERSAVE Network Event,
26 <http://www.watersave.uk.net/Presentations/Chris_Shirley-Smith.pdf>, (Oct. 20, 2008).
- 27
28
29 Shirley-Smith, C. and D. Butler (2008). Water management at Bedzed – Some lessons.
30 *Proceedings ICE Engineering Sustainability*, 161, 2, ES1, pp. 113-122.
- 31
32 Sostar-Turk S., Petrinic, I. and Simonic, M. (2005). Laundry wastewater treatment using
33 coagulation and membrane filtration, *Resources, Conservation and Recycling*, 44, 2, pp.
34 185-196.
- 35
36
37 South West Water (2009). "Charges and Tariffs 2009/10", <
38 <http://www.southwestwater.co.uk/media.cfm?mediaid=3320>>, (Sep. 1, 2009).
- 39
40
41 Srdjevic, B. (2007). Linking analytic hierarchy process and social choice methods to support
42 group decision-making in water management, *Decision Support Systems in Emerging*
43 *Economies*, 42, 4, pp. 2261-2273.
- 44
45 UK Office of National Statistics (2009). *Financial Statistics No. 568 August 2009*, p. 149.
- 46
47 Vorosmarty, C.J., Green, P., Salisbury, J. and Lammers, R.B. (2000). Global water resources:
48 Vulnerability from Climate Change and Population Growth, *Science*, 289, 5477, pp. 285-
49 288.
- 50
51 Vose R.S., Schmoyer, R.L., Steurer, P.M., Peterson, T.C., Heim, R., Karl, T.R. and Eischeid,
52 J. (1992). The Global Historical Climatology Network: long-term monthly temperature,
53 precipitation, sea level pressure, and station pressure data. Carbon Dioxide Information
54 Analysis Center, Oak Ridge National Laboratory, ORNL/CDIAC-53, NDP-041,
55 <<http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.GHCN/>>, (Oct. 10, 2008).
- 56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Ward, M.O. (1994). XmdvTool: integrating multiple methods for visualizing multivariate data, Proceedings of the conference on Visualization'94, Washington D.C., 17-21 October 1994.