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Design robustness of local water-recycling schemes

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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 possibility of re-engineering the urban water cycle to implement water recycling and reuse practices (Hurley et al. 2007; Liu et al. 2006; Makropoulos et al. 2006). Examples of these new practices are the use of treated greywater (or "greenwater") for a variety of non-potable water uses in the household (Dixon et al. 1999; Leggett et al. 2001; Memon et al. 2007; Shirley-Smith 2005) and at larger scales (see review by Gikas and Tchobanoglous 2009). Experience suggests, however, that the successful design and implementation of these new practices is not always straightforward (Shirley-Smith and Butler 2008) and further support to practitioners is warranted, including, but not restricted[1] to, the development of dependable, user-friendly tools able to analyse/simulate the total water cycle.

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

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

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

[1] Clearly there are more barriers to the implementation of novel water practices than analytical and modelling tools' availability. For a review of relevant work see for example Brown, R., Farrelly, M. and K. Nina (2009).

assessment tool. The optimisation results from the Mediterranean climatic conditions were assessed under a potential reduction of the annual precipitation providing an estimate of the influence of changes in climatic conditions on the PF solutions.

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

Description of UWOT

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

1. **Lower level**. This level includes the individual household water appliances (e.g. toilets, washing machines, local treatment units).
2. **Middle level**. This level includes the households as well as "central" technologies (i.e. technologies such as centralised greywater treatment, centralised wastewater treatment or a development scale drainage system). Each household includes (a) water using appliances, (b) in-house water infrastructure (greenwater tanks, pipeworks) and (c) a set of characteristics that affect the water budget (occupancy, pervious/impervious area).
3. **Higher level**. The higher level is the urban development as a whole. An urban development could range from a new neighbourhood to a new village or small town. An urban development is defined by the number of household types included in the development, the public pervious/impervious areas of the development and the type of the recycling/treatment scheme.

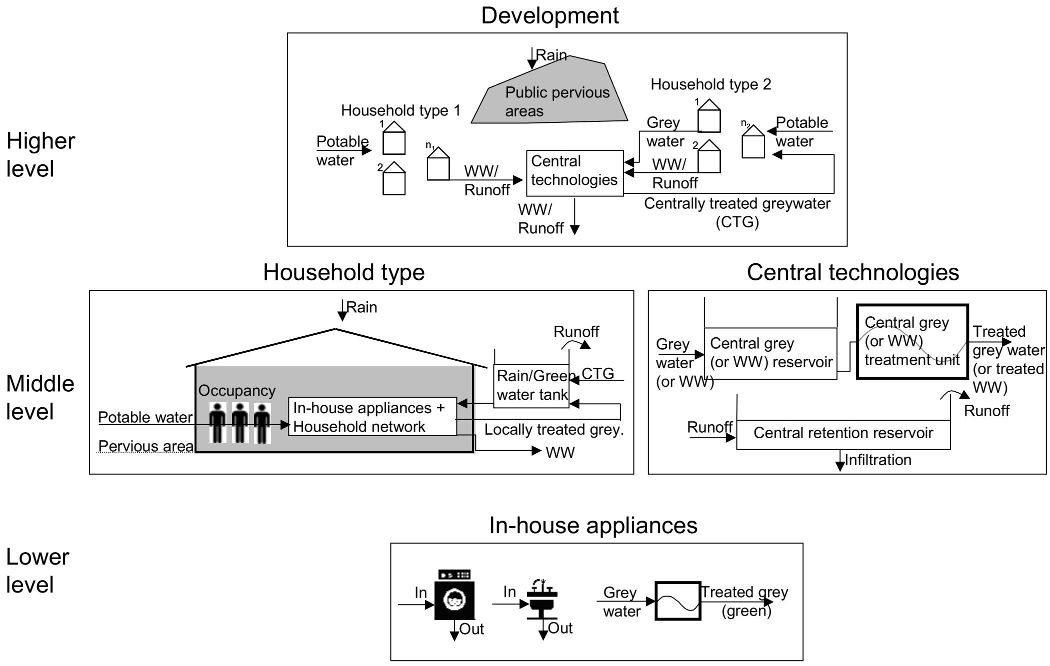

Figure 1: Hierarchical representation of the water system of an urban development in UWOT.

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.

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

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

Optimisation algorithm

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

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

UWOT Application

In this paper two hypothetical water saving schemes employing local recycling and water reuse techniques were studied:

The first scheme is depicted in Figure 2. In this scheme the harvested rainwater (R_t is the harvested rainfall volume during the time interval t from the rainwater harvesting area Ah) is stored in a local tank and used for toilet flushing, washing machine and outside uses (Yn_t is the water yield volume from local tank during the time interval t). This should be considered realistic as work has shown that use of rainwater within the household does not generally have adverse (health or technical) effects (e.g. for use of rainwater in washing machines see Herrmann and Schmida (2000)). Clearly local characteristics of the rain and of the roofs or collecting areas need to be taken into account, but health impact assessment studies have shown rainwater harvesting to be a low risk water source (Heyworth et al. 2006; Fewtrell and Kay 2008). The rest of the appliances are supplied with potable water from water mains (Mp_t is the potable water volume supplied from the mains to the household during the time interval t). Potable water from the mains is also used to ensure that the water level (Vn_t is the water volume in store at the beginning of the time interval t) in the local tank does not drop under a minimum threshold (Vmin). If the water level exceeds the local tank capacity (Sn) the surplus water is spilled (On_t is the overflow volume from the local tank during the time interval t) into the rainwater drainage system. The output of all local appliances is considered wastewater and is sent to the wastewater drain (WW_t is the wastewater volume produced from the household during the time interval t).

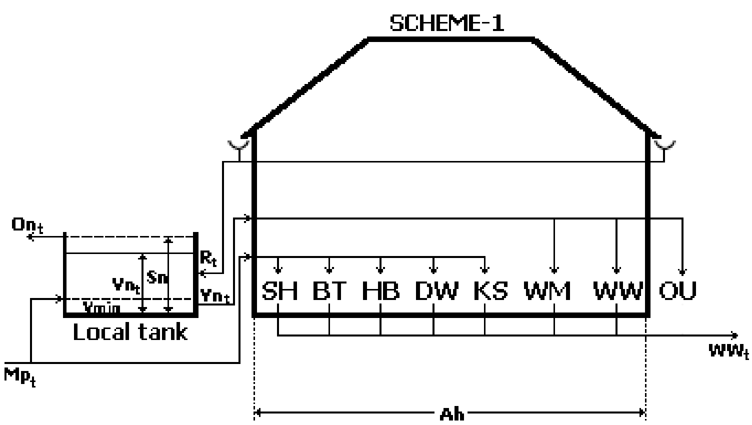

Figure 2: Schematic representation of water saving scheme-1. SH for shower, BT for bath, HB for hand basin, DW for dish washer, KS for kitchen sink, WM for washing machine, WW for toilet and OU for outside uses

The second scheme is depicted in Figure 3. The difference from the previous scheme is that greywater from the shower, bath and hand basin (Lr_t is the greywater volume from the household appliances during the time interval *t*) is treated locally and stored in a local tank (Ln_t is the treated greywater volume from the local greywater treatment unit during the time interval *t*) along with the harvested rainwater. Organic sediments and particles are filtered out in the local greywater treatment unit and diverted into the wastewater drain (Or_t is the volume of the excess greywater plus water losses and by-products from greywater treatment during time the interval *t).* The water losses and flow of by-products was assumed here (conservatively) to be 3% of the incoming flow, as an example. This value is a function of the efficiency of the particular treatment technology used and can be specified by the user through UWOT's technology library.

The treatment process included in this specific scenario comprises of four treatment stages: Initially the incoming greywater is filtered and then two stages of bio-mechanical cleaning process follow. Finally the water is sterilized using UV. It is suggested that this level of treatment is feasible and given the sources of greywater in our scenario, and its eventual mix with rainwater, the resulting water quality should be quite adequate for the investigated uses (toilet flushing, washing machine and outside uses).

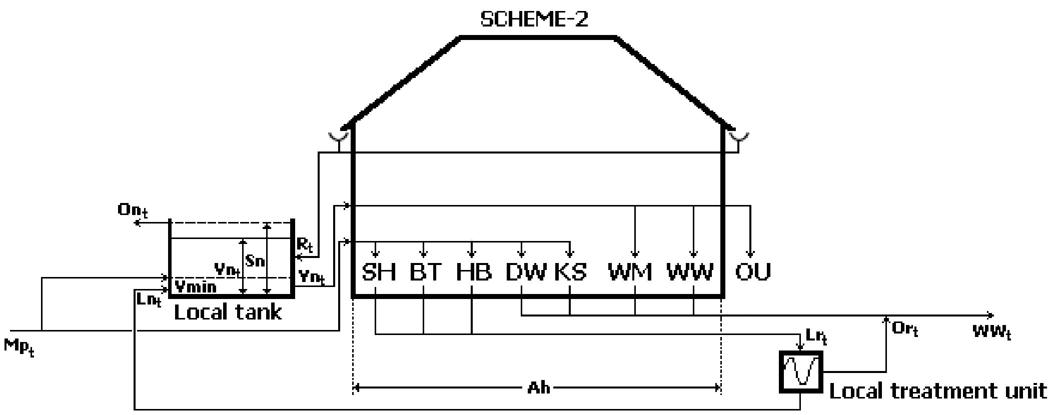

Figure 3: Schematic representation of water saving scheme-2.

To increase optimisation speed and simplify the modelling exercise, a test development with only one household is investigated in this study (an unrestricted, user-defined number of houses can be simulated by UWOT, with household results aggregated at the development scale). This household was assumed to have 130 m^2 of rainwater harvesting area and 4 occupants (i.e. the typical 4 bedrooms household of the Elvetham Heath development in the UK (Parsons and Sim 2007)).

The simulation time step was daily (see Makropoulos et al. (2009) for a discussion on the effect of daily time steps on realistic representations of the urban water cycle) and the simulation period length was five years (five years with daily time step is the maximum number of simulation time steps allowed by the current model version). The two schemes were examined using three time series of daily rainfall obtained from the Freemeteo[2] database. The first time series is recorded from a meteorological station in London Heathrow Airport, the second from a meteorological station in Paphos Airport in Cyprus and the third from a meteorological station in Qatar's Doha Airport. All time series start at 1 October 2000 and end at 30 September 2005. The average monthly rainfall and the average rainfall events per month at these locations (for this specific 5-year period) are displayed in Figure 4 (Vose et al. 1992). The corresponding annual precipitations at Heathrow, Paphos and Doha airports are 671.34 mm, 433.8 mm and 61.5 mm respectively.

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

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

[2] freemeteo.com (Retrieved at 25 October 2008)

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

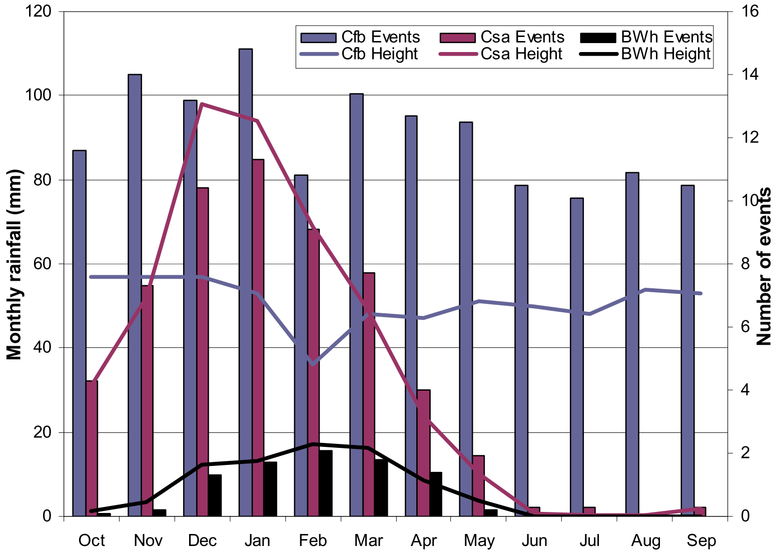

Figure 4: Monthly rainfall characteristics of Cfb, Csa and BWh climatic conditions. Cfb, Csa, BWh Events: the average number of rainfall events per month in the Cfb, Csa, BWh climatic conditions. Cfb Csa, BWh Height: the average monthly rainfall depth per month in the Cfb, Csa, BWh climatic conditions.

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

Table 2: NSGA-II algorithm parameters

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

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

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

- type of water appliances used in the household (in each of the six household "types" UWOT supports).
- percentage of impervious/pervious/rainwater-harvesting areas
- type of water recycling scheme (at the household or development scale)

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

Results

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

The parameter to be optimised in scheme-1 (tank capacity) influences only two out of the four objective functions (specifically capital cost and potable water demand since greenwater is assumed to be supplied by gravity eliminating any requirements for energy and operational cost). The trade-off between capital cost and potable water demand reduction for scheme-1 for Cfb, Csa and BWh climatic conditions is displayed in Figure 5. The percentage increase of the capital cost is calculated with respect to the capital cost of a conventional water system (no water recycling/reuse). All curves in Figure 5 intersect the x-axis at 34%. This reflects capital cost increase due to the installation of the pipework (which is common to all solutions).

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

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

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

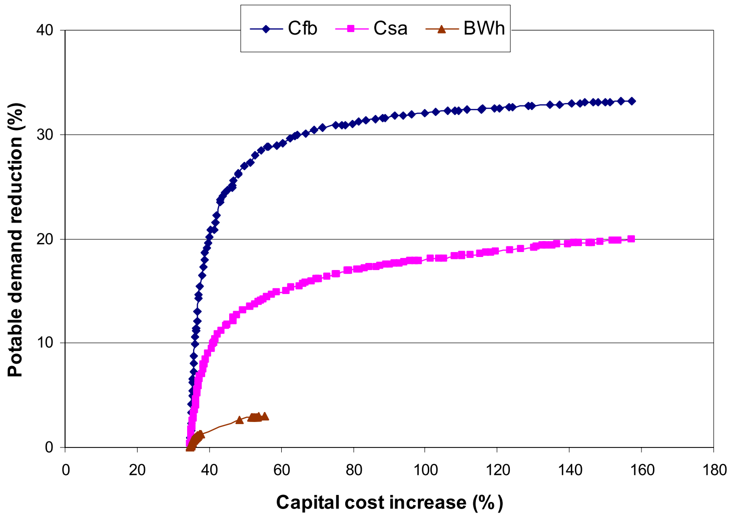

Figure 5: Potable water demand reduction (%) versus capital cost increase (%) of scheme-1 under Cfb, Csa and BWh climatic conditions.

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

In the present case study the four objective function values differed by orders of magnitude and for this reason standardised values were used in the PCPs. The objective function values were standardised using the formula $(O_{ij}- \mu_j)/\sigma_j$ where: O_{ij} is the j^{th} objective-function value (j ranges from 1 to 4 where 4 is the number of the 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,..,70 and σ_j is the standard deviation of the O_{ij} for i=1,..,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.

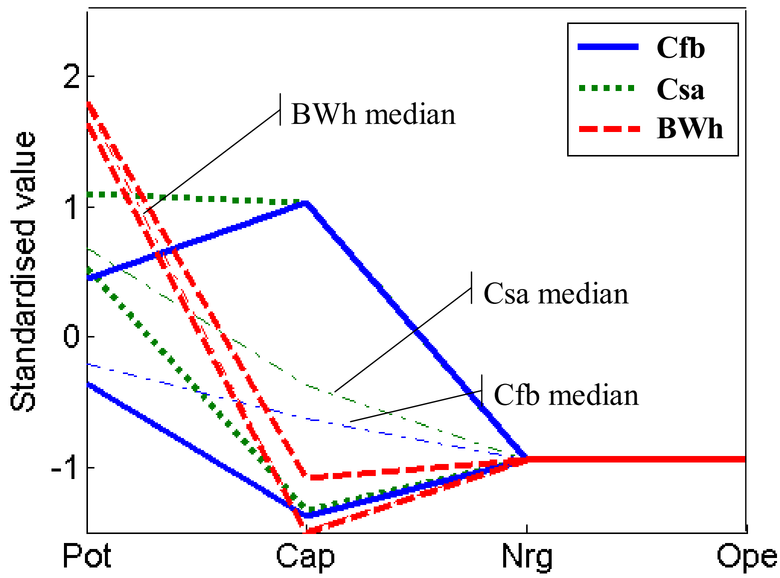

Figure 6: PCP of scheme-1 for Cfb, Csa and BWh climatic conditions. In the vertical axis the standardised values of the objective functions. Pot: the potable water demand; Cap: the capital cost; Nrg: the operational energy; Ope: the operational cost.

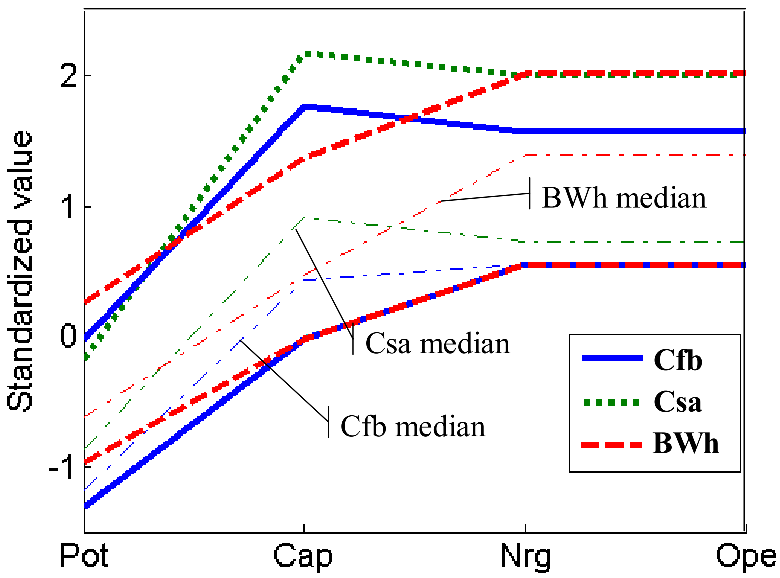

Figure 7: PCP of scheme-2 for Cfb, Csa and BWh climatic conditions. In the vertical axis the standardised values of the objective functions. Pot: the potable water demand; Cap: the capital cost; Nrg: the operational energy; Ope: the operational cost.

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.

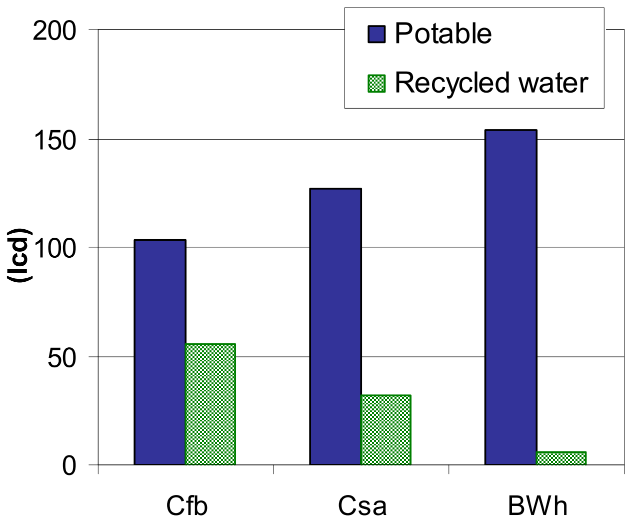

Figure 8: Consumption per water type of the scheme-1 PF solutions that achieved the minimum potable water demand under Cfb, Csa and BWh climatic conditions.

The consumption per water type of scheme-2 PF solutions that achieved the minimum potable water demand (regardless of the costs and energy) under Cfb, Csa and BWh climatic conditions is displayed in Figure 9. This figure suggests that scheme-2 achieved satisfactory water savings even in BWh climatic conditions. Recycled water (including both treated greywater and harvested rainwater) covers 47%, 47% and 42% of the water demand in Cfb, Csa and BWh climatic conditions respectively.

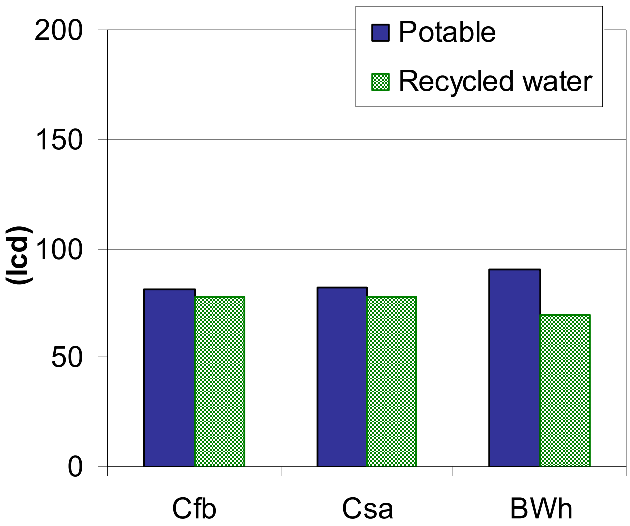

Figure 9: Consumption per water type of the scheme-2 PF solutions that achieved the minimum potable water demand under Cfb, Csa and BWh climatic conditions.

B. Stage 2: Impact of changes in climatic conditions

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

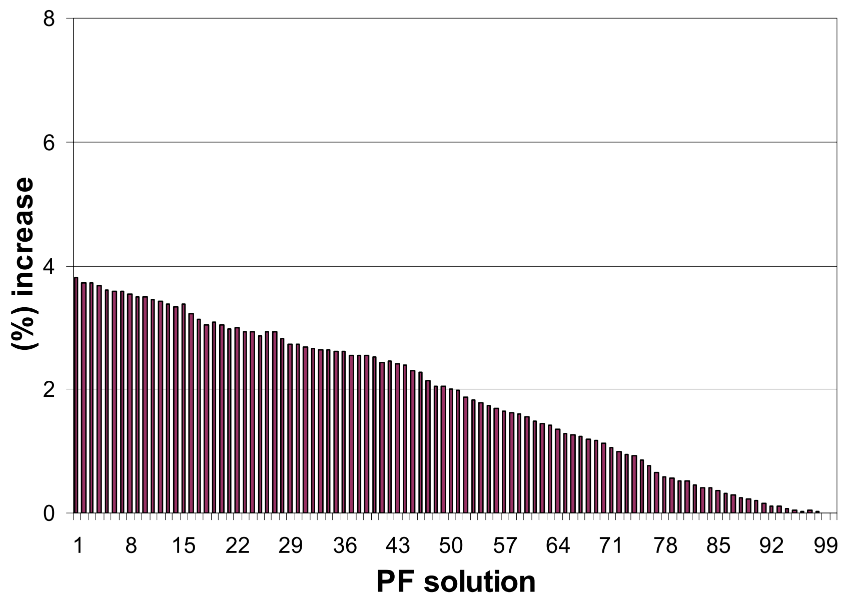

Figure 10: Percentage increase of the potable water demand of the scheme-1 PF solutions for Csa, assessed under reduction of annual precipitation by 20%.

The percentage increases of demand for potable water of the 70 scheme-2 solutions are shown in Figure 11. The maximum percentage increase is almost 1.5%.

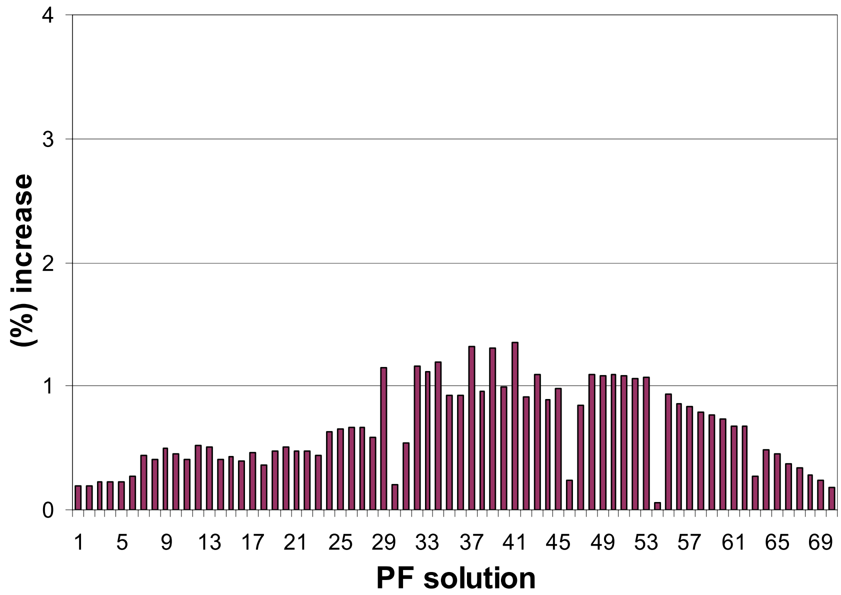

Figure 11: Percentage increase of the potable water demand of the scheme-2 PF solutions for Csa, assessed under reduction of annual precipitation by 20%.

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

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

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

where: D_{tot} the daily water demand [L^3], D_{grn} the daily green water demand [L^3], R_A the average daily harvested rainfall of the present climatic conditions [L^3], R_B the average daily harvested rainfall of the future climatic conditions [L^3].

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

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

B. Scheme-2

In Cfb climatic conditions, the average number of rainfall events per month varies between 10 and 15 (Figure 4) and the average monthly rainfall depth between 36 and 57 mm. This relatively uniform distribution of rainfall-events' frequencies and rainfall depths throughout the hydrological year, results in a sufficient amount of harvested rainwater. Only a limited extra supply from the local greywater treatment unit is required to cover the household demand for recycled water. This limited supply can be provided with low operational cost and energy consumption. This explains the proximity of the median values of energy and operational cost to the lower boundaries in Figure 7.

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

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

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

Figure 11 indicates that the scheme is hardly influenced by changes in climatic conditions.

Conclusions

Two water recycling schemes ((a) rainwater harvesting only and (b) rainwater harvesting plus local greywater treatment) were optimised for three climatic conditions (Cfb, Csa and BWh) using the UWOT decision support tool. A multi-objective optimisation approach was used to obtain a set of alternative solutions (Pareto front) for each climatic condition. The Pareto front solutions of the Csa climate were then examined under reduced annual rainfall by 20%, following IPCC recommendations. The results of this investigation can be summarised as follows:

1. A local rainwater harvesting scheme can only offer minor potable water demand reduction (3%) under BWh climatic conditions. The same scheme can provide a reduction to potable water demand by 20% in Csa climatic conditions but with a significant increase in capital cost (of the order of 160%). In Cfb climatic conditions a 30% reduction of demand for potable water can be achieved with an increase of capital cost by 64%. Assuming annual interest equal to 3% (average rate of interest on investment account for the period 2001-2007, UK Office of National Statistics 2009) and water price 1.6 £/m^3 (South West Water 2009) the payback period for this capital cost increase would be 25 years (the corresponding period, for capital cost increased by 64%, would be 40 years in Csa climatic conditions).
2. The combination of rainwater harvesting with a local greywater treatment unit can reduce the demand for potable water by more than 42% even in BWh climatic conditions. Furthermore, this scheme is hardly influenced by changes in climatic conditions. The disadvantage of this scheme is that both operational cost and required energy increase in climates with low annual precipitation. This is consistent with the trade-off identified between water and energy in urban water management for a given technological level (Butler and Makropoulos 2006).

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

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

Hurley, L., Mounce, S.R., Ashley, R.M. and Makropoulos, C.K. (2007). Support for more sustainable decision making in urban water management. CCWI07 Conference, Leicester, UK, September 2007.

Inselberg, A.and Dimsdale, B. (1990). Parallel coordinates: a tool for visualizing multidimensional geometry. Proceedings of the First IEEE Conference on Visualization, pp. 361-378.

Intergovernmental Panel on Climate Change (IPCC) (2007). Climate Change 2007: Synthesis Report, Spain.

Joksimovic, D. (2006). Decision support system for planning of integrated water re-use systems, Ph.D. thesis, University of Exeter, December 2006.

Kapelan, Z.S., Savic, D.A. and Walters, G.A. (2003). Multiobjective Sampling Design for Water Distribution Model Calibration, J. Water Resour. Plng. and Mgmt. 129, 6, pp. 466-479.

Leggett, D.J., Brown, R., Brewer, D., Stanfield, G. and Holliday, E. (2001). Rainwater and greywater use in buildings: best practice guidance, CIRIA publication C539, London, ISBN: 0860175397.

Liu, S., Makropoulos, C.K, Memon, F.A. and Butler, D. (2006). An object based household water cycle model: concept and construction, Water Practice and Technology, IWA online journal, 2, 2.

Makropoulos, C. K., Rozos, E. and Butler, D. (2009). Urban Water Modelling And The Daily Time Step: Issues For A Realistic Representation, 7th ISE & 8th HIC, Concepción, Chile, 2009.

Makropoulos, C. K., Natsis, K., Liu, S., Mittas, K., and Butler, D. (2008). Decision Support for Sustainable Option Selection in Integrated Urban Water Management, Environmental Modelling and Software, 23, 12, pp. 1448-1460.

Makropoulos, C.K., Morley, M., Memon, F.A., Butler, D., Savic, D. and Ashley, R. (2006). A Decision Support Framework for Sustainable Urban Water Planning and Management in New Urban Areas, Water Science & Technology, 54, 6-7, pp. 451-458.

March, J.G, Gual, M. and Orozco F. (2004). Experiences on greywater re-use for toilet flushing in a hotel (Mallorca Island, Spain), Desalination, 164, pp. 241-247.

Marshallsay, D., Trew, J. and Waylen C. (2007). Assessing the cost of compliance with the code for sustainable homes, UK Environment Agency.

Memon, F.A. , Zheng, Z., Butler, D., Shirley-Smith, C., Liu, S. Makropoulos, C.K. and Avery, L. (2007). Life cycle impact assessment of greywater treatment technologies for new developments, Journal of Environmental Monitoring and Assessment, 129, 1-3, pp. 27-35.

Ningchuan, X., Bennett, D.A. and Armstrong ,M.P. (2007). Interactive evolutionary approaches to multiobjective spatial decision making: A synthetic review, Computers, Environment and Urban Systems, 31, 3, pp. 232-252.

Parsons, J. and Sim, P. (2007). WaND briefing note 25, Elvetham Heath Developer Survey.

Peel, M. C., Finlayson, B. L. and McMahon, T. A. (2007). Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci., 11, 5, pp. 1633-1644.

Pontos (2008). "Technical data AquaCycle 900", <http://www.pontos-aquacycle.com/pontos/en/>, (Oct. 28, 2008).

Rosegrant, M.W., Cai, X. and Cline, S. (2002). World Water and Food to 2025, International Food Policy Institute, Washington, DC, p. 5.

Sakellari, I., Makropoulos, C., Butler, D. and F. A. Memon (2005). Modelling sustainable urban water management options. Proceedings of ICE, Engineering Sustainability, 158, 3, pp 143-153.

Shirley-Smith, C. (2005). The sustainability value of the green roof water recycling system in urban communities, WATERSAVE Network Event, <http://www.watersave.uk.net/Presentations/Chris_Shirley-Smith.pdf>, (Oct. 20, 2008).

Shirley-Smith, C. and D. Butler (2008). Water management at Bedzed – Some lessons. Proceedings ICE Engineering Sustainability, 161, 2, ES1, pp. 113-122.

Sostar-Turk S., Petrinic, I. and Simonic, M. (2005). Laundry wastewater treatment using coagulation and membrane filtration, Resources, Conservation and Recycling, 44, 2, pp. 185-196.

South West Water (2009). "Charges and Tariffs 2009/10", < http://www.southwestwater.co.uk/media.cfm?mediaid=3320>, (Sep. 1, 2009).

Srdjevic, B. (2007). Linking analytic hierarchy process and social choice methods to support group decision-making in water management, Decision Support Systems in Emerging Economies, 42, 4, pp. 2261-2273.

UK Office of National Statistics (2009). Financial Statistics No. 568 August 2009, p. 149.

Vorosmarty, C.J., Green, P., Salisbury, J. and Lammers, R.B. (2000). Global water resources: Vulnerability from Climate Change and Population Growth, Science, 289, 5477, pp. 285-288.

Vose R.S., Schmoyer, R.L., Steurer, P.M., Peterson, T.C., Heim, R., Karl, T.R. and Eischeid, J. (1992). The Global Historical Climatology Network: long-term monthly temperature, precipitation, sea level pressure, and station pressure data. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, ORNL/CDIAC-53, NDP-041, <http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.GHCN/>, (Oct. 10, 2008).

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.