

Water recycling at the Millennium Dome

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Abstract Thames Water is working with the New Millennium Experience Company to provide a water recycling system for the Millennium Dome which will supply 500m³/d of reclaimed water for WC and urinal flushing. The system will treat water from three sources:

- rainwater – from the Dome roof
- greywater – from handbasins in the toilet blocks
- groundwater – from beneath the Dome site

The treatment technologies will range from “natural” reedbeds for the rainwater, to more sophisticated options, including biological aerated filters and membranes for the greywater and groundwater. Pilot scale trials were used to design the optimum configuration. In addition to the recycling system, water efficient devices will be installed in three of the core toilet blocks as part of a programme of research into the effectiveness of conservation measures. Data on water usage and customer behaviour will be collected via a comprehensive metering system.

Information from the Dome project on the economics and efficiency of on-site recycling at large scale and data on water efficient devices, customer perception and behaviour will be of great value to the water industry. For Thames Water, the project provides vital input to the development of future water resource strategies.

Keywords Recycling; nonpotable; reuse; reclamation; efficiency; perception; greywater

Introduction

With the approach of the new Millennium, the need for water utilities to further address sustainable water use became ever more pressing. Historically, in the UK there has been little need to consider options such as in-building recycling. However, the implications of changing lifestyle patterns, increasing customer expectations, the requirement for an extra 4 million new homes in Britain and the influence of climate change, mean that water resources will be ever more stretched. Existing water supplies must be sustainable into the next century unless alternative sources are identified. The use of new and existing technology, coupled with a change in the public’s behaviour to water conservation is seen as necessary to cope with the present and future increase in water demand.

As part of its water resources strategy Thames Water is investigating a number of options including additional reservoirs, metering, aquifer storage and other novel solutions. In accordance with this strategy, Thames Water in association with the New Millennium Experience Company (NMEC) implemented the first major in-building recycling scheme in the UK. The system was constructed at the Millennium Dome, Greenwich which was to be the focus of the country’s millennium celebrations. At a cost of £758 million, the Dome is the largest building of its kind in the world with a perimeter of 1km, an apex of 50m. An estimated 12 million people were expected to visit the Dome during the year 2000 (NMEC Annual Report, 1998).

A key strand of the Dome’s environmental policy has been the innovative approach to water management and the implementation of a major on-site recycling scheme collecting and treating water from three sources to flush all the WCs and urinals on the site. The water recycling plant included a visitors centre to impart key messages on water conservation and

efficiency. The toilet blocks were fitted with a variety of water efficient devices as part of a large public participation experiment into water efficiency. The scheme included a comprehensive metering programme so that reductions in water usage can be calculated.

Methodology

Identifying the water sources for recycling

The Dome has a maximum requirement of 500m³/d for WC and urinal flushing. Three potential sources of secondary water for recycling to meet this demand were identified on site.

Rainwater. The surface area of the Dome roof is 100,000 m², so there is the potential for huge quantities of rainwater run-off during rain storms. Rain runs from the roof through specially designed hoppers which feed into the surface water drainage system. Although the potential volumes of rain are high, the constraints of the site mean that the area available for storage is restricted. It was calculated that a maximum flow of 100 m³/d (1mm/d rainfall) could be accommodated, so a system was designed to divert and collect this volume.

Greywater. The Dome has six core buildings that house the toilet blocks and greywater will be collected from the handbasins. The expected 35,000–55,000 visitors each day and staff were predicted to use, on average, 120 m³/d of handbasin water which could then be treated and reused. This figure was the best estimate based on available information including CIBSE (The Chartered Institution of Building Service Engineers) design recommendations (CIBSE Guide, 1986) and studies of handbasin water demand in domestic situations (Butler *et al.*, 1995; Rose, 1991).

Rising groundwater. London, like many other metropolitan cities, has a problem with rising groundwater. Historical over-pumping for industrial and commercial supply from the chalk had reduced natural groundwater levels by over 50 m. However, since 1970 declines in these pumping rates due to the changing industrial base of London has allowed a rapid recovery of water levels. Groundwater levels have, consequently, already risen by over 35 m over the last 20 years with rates of rise under the City of London and Westminster of over 2 m per year (see Figure 1).

GARDIT (General Aquifer Research and Development Investigation Team) is a multi-organisational grouping set up to look at the problem of London's rising groundwater. It has identified potential borehole locations around the Thames Water region where pumping from the aquifers would be beneficial. The Greenwich peninsular had already been identified as one of these areas (GARDIT Update, 1996).

Rising groundwater was, therefore, identified as the third source of water necessary to achieve the flushing volumes required at the Dome. A 110 m borehole was drilled on the site and pumping tests for quality and quantity completed.

Designing the treatment plant

Thames Water has been researching treatment technologies for non-standard waters for a number of years in anticipation of future water demand requirements. The options have ranged from pilot scale in-building greywater treatment technologies, such as membrane bioreactors (Jefferson *et al.*, 1998) to larger scale reverse osmosis (RO) membrane plants for brackish waters. The Dome project provided the opportunity to implement a reuse scheme at full scale and demonstrate a range of treatment options from these innovative technologies to "natural" managed wetlands.

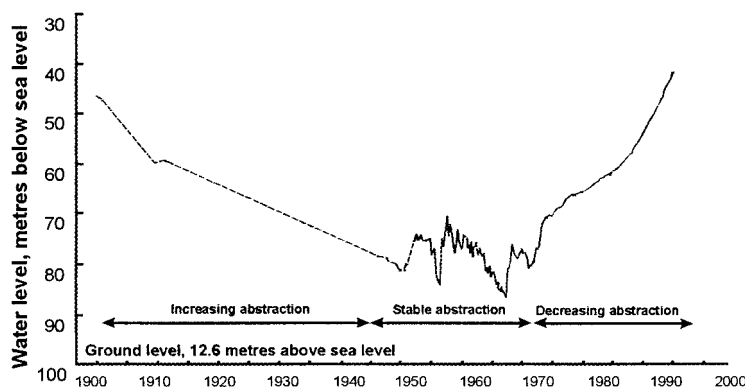


Figure 1 Water table levels below Trafalgar Square, London since 1900

Reedbeds – rainwater treatment. Reedbeds were the treatment choice for the rainwater as the runoff from the Dome roof was predicted to be of good quality and the precaution of avoiding the, potentially more contaminated, “first flush” was included in the design.

The rainwater is passed through a series of reedbeds and a lagoon which form part of the landscape design. The first reed bed is designed for stormwater treatment at $2.5 \text{ m}^3/\text{m}^2/\text{d}$. Following this is a storage lagoon of approximately 300 m^2 . The second reedbed will perform a tertiary treatment function. Each reed bed has an area of 250 m^2 and is designed for a maximum flow of $100 \text{ m}^3/\text{d}$. All flows beyond this will be discharged to the River Thames. The beds are approximately 0.6 m deep and have a 0.5% gradient. The media is washed river gravel of $5\text{--}10 \text{ mm}$, planted with the common reed, *Phragmites australis*, and grown from an appropriate seed to ensure salt tolerance (Cooper *et al.*, 1996).

Greywater – Biological Aerated Filter (BAF) & membrane pilot trials. The primary concern for the treated greywater was that it met the quality criteria for pathogen kill. Another key concern was ensuring that the potential for biological regrowth in the reclaimed water distribution system was minimal. An estimate of the potential for regrowth can be gained by considering total and soluble biochemical oxygen demand (BOD) in the reclaimed water. A survey showed that world-wide recommendations for total BOD for flushing purposes range from 2 mg/l to $< 20 \text{ mg/l}$ (Crook, 1991; Kayaalp, 1996; Tay and Chui, 1991).

Based on previous work, the proposed treatment for the handbasin greywater was biological treatment in a Biological Aerated Filter (BAF) followed by membranes (Jefferson, 1998). In order to ascertain the optimum configuration of these processes a range of pilot trials were undertaken with specific emphasis on BOD removal (Birks, 1998). The performance of a pilot scale BAF, followed by a variety of membranes was investigated using synthetic greywater. The BAF comprised two downflow columns, each with a diameter of 150 mm , a height of 2 m , and a total bed volume of 0.036 m^3 . Lytag pulverised fuel ash media was used in both columns. The membrane test rig consisted of six single tubes, with a total membrane area of 0.22 m^2 and was operated in batch mode with a variety of ultrafiltration (UF), nanofiltration (NF) and RO membranes. The greywater feed quality was established from previous work (Christova-Boal *et al.*, 1996; Murrer and Bateman, 1998) and a manufacturers survey of soaps and detergents which confirmed that all handwash soaps are significantly biodegradable and also revealed that the majority of modern soaps supplied for large scale public application use synthetic surfactants (Birks, 1998).

Table 1 shows that all of the membranes tested achieved a BOD reduction within the 2 to $< 20 \text{ mg/l}$ BOD recommended ranges. The pilot scale trials indicated that tight UF mem-

Table 1 BOD reduction following BAF and membrane treatment

	greywater influent	BAF effluent	UF open	UF tight	NF	RO		
			1	2	3	4	5	6
Membrane type								
total BOD (mg/l)	60	20–25	10.6	5.1	6.3	3	2.3	4.8
soluble BOD (mg/l)	30	6–10	8.3	4.7	5.8	3.1	2.4	4.7

Key:

membrane type	Material	rejection characteristics	product name
1	Polyvinylidenefluoride	MWCO 200,000 Daltons	FP 200
2	Modified polyethersulphone	MWCO 6,000 Daltons	EM 006
3	Polyethersulphone	MWCO 4,000	ES 404
4	Polyamide film	75% CaCl ₂ rejection	AFC 30
5	Polyamide film	80% NaCl rejection	AFC 80
6	Cellulose acetate	90% NaCl rejection	CDA 16

branes were the most appropriate option for handbasin greywater treatment, however, before a final decision on membrane type was made the quality of the other source waters had to be considered.

Groundwater quality. Water from the borehole was tested to establish the groundwater quality. It had been found by the GARDIT group that borehole water quality could vary markedly from site to site. From the outset, a problem with hydrogen sulphide gas was experienced. Subsequent analysis of the water also indicated a much higher salt content than anticipated (total dissolved solids (TDS) > 2000 mg/l; see Table 2) plus organic contamination and high iron content. Table 2 shows how the quality of the Dome borehole water varied markedly from another borehole of only 250 m away.

Treatment process. Following the pilot trials and water quality analysis, the treatment process configuration was chosen (see Figure 2). The groundwater is pumped to the surface and initially dosed with hydrogen peroxide to oxidise hydrogen sulphide and ferrous iron. The water then passes through granular activated carbon (GAC) to remove the organic contaminants. Membrane filtration follows the GAC where Ultrafiltration removes suspended particles including bacteria and viruses and reverse osmosis membranes remove the salt present in the groundwater. The groundwater, treated greywater and the rainwater from the reedbeds are treated through the same membrane configuration. The product water is re-hardened and disinfected before being pumped back into the Dome for flushing the WCs and urinals. The water quality will exceed current draft UK standards for flushing (BSRIA Report, 1997).

Table 2 Groundwater quality at 2 Greenwich sites

determinand	Units	groundwater quality (averages)	
		Dome borehole	Adjacent site (250m)
pH		7.4	7.7
conductivity	µS/cm	3792	946
turbidity	Formazin	36.7	2.8
hardness	mg/l as CaCO ₃	758	204
iron	µg/l	1711	461
chloride as Cl	mg/l	1155	81.5
sulphate as SO ₄	mg/l	193	32
sodium	mg/l	588	61.4
TDS	mg/l	2438	620.5

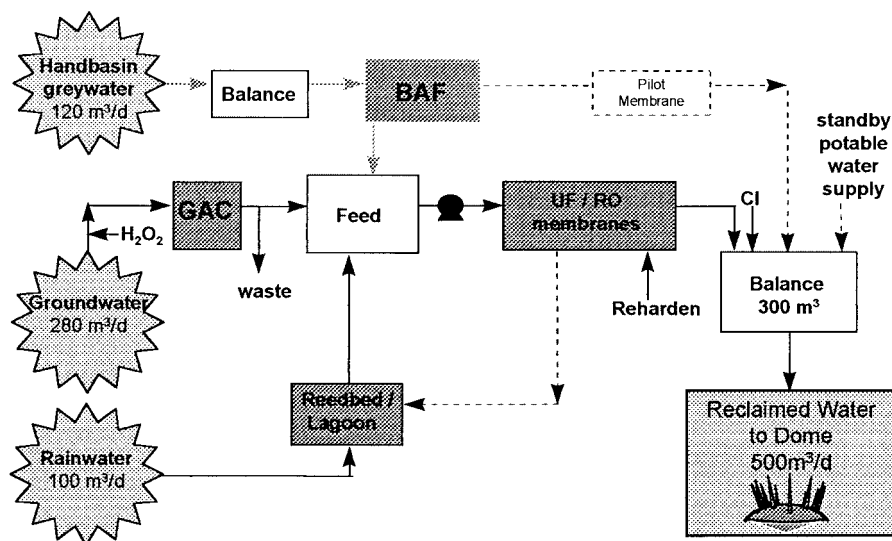


Figure 2 Schematic of treatment process

Collection and distribution pipework

In each of the six core buildings there are large male and female washrooms on both the ground and first floors. There are also a number of other toilet facilities for operations staff and performers within the Dome and a number of other external buildings. To accommodate the recycling system, it was necessary to adapt the planned pipework services to these buildings. The specification was developed with reference to examples from overseas, particularly the US, where dual reticulation systems are more common (BSRIA Report, 1997; American Water Works Association, 1994).

Greywater collection and reclaimed water distribution. The greywater from 360 handbasins in the toilet blocks housed in the six core buildings has been separated from the foul water drainage system. This greywater is transported to the treatment plant via a cascade pumping system. The reclaimed water distribution pipework required a protocol to be developed as there is no current standard in the UK for reclaimed water pipework markings. Purple pipe, the colour of choice for the US, was already in use for another service, so the use of black and green coding and the identifier “reclaimed water” was adopted. For the external pipework specially colour-coded medium density polyethylene (MDPE) was specified from the manufacturer. This was black with 4 green stripes and stamped with the words “reclaimed water”. For the internal reclaimed water pipework, which was copper, a colour-coding based on the British Standard (BS) for insulated pipes was developed using black and green secondary identification markers and the addition of the words “reclaimed water”. Figure 3 details the internal and external pipe identification.

The reclaimed water distribution system was designed to supply a maximum of 500 m³/d to flush WCs and urinals in all the buildings on the site. The reclaimed water is pressured to 6bar and then distributed in 180–60 mm MDPE pipework in a circumferential trench within the Dome and then onward to other outlying buildings. The use of pressure reducing valves (PRVs) is integral to the hydraulic design of the system to ensure that peak flushing demands can be accommodated.

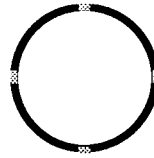
Internal pipework



External pipework



longitudinal view



transverse section

Key - Internal



Key - External

- LONGITUDINAL GREEN STRIPE AT EACH QUADRANT
- 'RECLAIMED WATER' STAMPED ON THE PIPE (as per pressure and temperature ratings)

Figure 3 Reclaimed water pipework identification at the Dome

Designing of the water efficient research programme

The recycling plant at the Millennium Dome was the hub of Thames Water's research into water reuse and conservation. It was staffed by full-time Thames Water research scientists as well as students from academic institutions with which Thames Water have on-going research collaboration. The research covered a number of areas including technical evaluation of the treatment processes, appraisal of water efficiency on the site and public attitudes towards recycling and conservation.

Treatment technology. A programme of research was drawn up to evaluate the various unit processes. Some of the key issues addressed included the water quality achieved by the different technologies, their reliability and operating costs. The ability to trial other membrane configurations in pilot side-stream units had been designed into the treatment plant. The quantities and qualities of the different recycling source waters were also to be evaluated.

Water efficient appliances. As the toilet blocks in the six core buildings are identical they provide the ideal venue for comparative research into water efficient appliances. As part of the overall scheme, a variety of water saving devices were installed. One "super efficient" block contained waterless urinals, infra-red controlled taps and dual flush cisterns (3 & 6 l). These were compared with the control cores using 6 l syphonic flush cisterns, standard urinal flushing systems and push-top taps (see Figure 4). The installation of dual flush cisterns required Bylaws relaxation from the Department of Environment Transport and the Regions.

Public perception. Two "behaviour" toilet blocks were fitted with identical technology; dual flush cisterns and basic on/off taps (see Figure 4). However, one of these blocks displayed educational messages regarding water saving and the other did not. This was aimed at ascertaining the influence, if any, of education on visitor-behaviour towards water conservation. The treatment plant itself was also used to educate the public. A viewing area enabled the public to learn more about water recycling issues and see for themselves the treatment technology in operation.

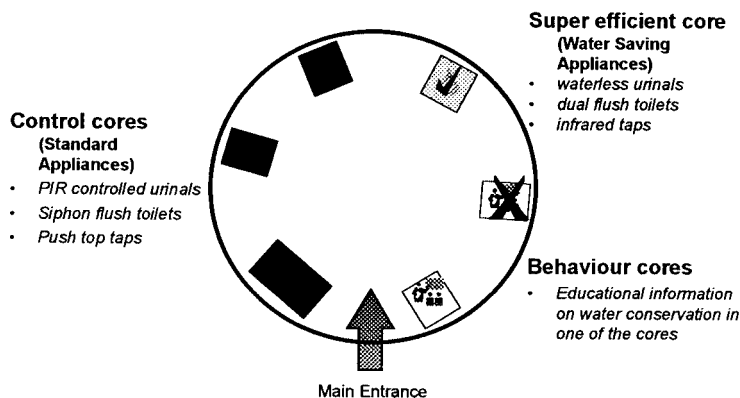


Figure 4 Schematic of the Millennium Dome toilet blocks showing the water saving and standard appliances installed

Monitoring water use. To monitor the water use, and ascertain the efficiency of the recycling system and the water saving technology, Thames Water installed a comprehensive metering system so that any reductions in water usage can be calculated. The metering scheme was to monitor hot, cold and reclaimed water flows to each toilet block. Both the male and female toilets were metered so that any differences in water use between the sexes could be monitored. Over 100 meters in total were installed on site and door counters were monitored the number of visitors to each toilet so that the average consumption per person could be calculated.

Discussion

The fast-track nature of the project required a flexible approach. Team work within both Thames Water and NMEC, and across all the suppliers, consultants and contractors was essential to ensure that the project progressed to programme. Many activities had to take place in parallel. For example, the construction of the pipework had to be undertaken to coincide with the other groundworks on site, and therefore many assumptions on flows had to be made in advance of full information being available. Additional buildings were designed to surround the Dome which significantly increased the number of toilets to be flushed with reclaimed water over the original estimate.

A design which allowed flexible operation of the treatment process was also essential. The plant would allow water to be taken from each of the three sources as appropriate. Due to the nature of the climate in South East England, rain is not reliable, so the ability to take groundwater from under the site was vital. However, the criticality of source water quality was highlighted by the experiences with the poor quality of the borehole water. A second major consideration with plant design was the high profile nature of the location and the need to minimise risk. This resulted in a robust design which is fail safe with a link to an emergency mains water supply if necessary.

During the lifetime of the *Millennium Experience*, the plant will be fully evaluated under operational conditions. One of the key areas is to establish the appropriateness of this type of recycling scheme, both in terms of reliability and cost effectiveness. The results will be compared with the other examples world-wide where the higher cost of potable water may have a significant effect on the long-term feasibility, of such schemes, in contrast with the UK where water is relatively cheap. In-building recycling examples are few and mainly in Japan, whereas, although there are a number of high profile dual reticulation schemes in the US, these are at a larger, municipal scale. Many of the surveys on public perception of water

recycling, similarly, have come from the US and this study has aimed to increase understanding of public attitudes in a UK context.

Conclusions

In summary, the implementation of a recycling scheme at the Millennium Dome site with the potential to use the venue for on-going public education and academic research into water efficiency and conservation has been seen as a major opportunity, not only for the UK water industry, but for others with an interest in sustainable water management into the next century.

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