Sustainable water: Chemical science priorities

Introduction to report

Purpose of the report

This report highlights the key role of the chemical sciences in driving future developments in water management, nationally and internationally. The report's scope encompasses the entire hydrological cycle with an emphasis on human activity, particularly on managing domestic, industrial and agricultural water use, contamination, and climate change. The report summarises the current situation and recommends future developments as well as the processes needed for these to be realised.

The report is intended to provide guidance to policy makers and funding bodies on the challenges and key priority areas for the chemical sciences, across the hydrological cycle, that will deliver the technologies, infrastructure, skills and stakeholder education for sustainable water management. The report focuses on presenting sound scientific evidence to support its key recommendations.

This document is a summary of the key findings and the report's recommendations. The full report is available on the RSC website www.rsc.org/water.

Introduction

The majority, 97%, of water on Earth is saline and without energy intensive desalination technology is non-potable. Of the 3% that is freshwater, two thirds is locked away glaciers and the polar ice caps. Humanities needs therefore must be met with only 1% of the Earth's total water. Of this the majority is groundwater, with 0.3% as surface water and only 0.04% present in the atmosphere (see Chapter 1).

In addition to drinking water humanities needs are essentially threefold. Firstly, agriculture requires vast amounts of water for crop irrigation; in fact 70% of the global water demand arises from agriculture. Secondly, domestic living requires water for cooking, cleaning and flushing toilets. Finally, industrial processes require water as a feedstock, as a solvent, to raise steam, as a coolant and to clean (see Chapter 2).

The water resources available to meet these demands comprise surface water and groundwater. Surface water is that which is contained in rivers, lakes and wetlands, and can also include artificial reservoirs. Easily accessible, it is replenished through rainfall and depleted through, not including human usage, evaporation into the atmosphere, eventual discharge into the oceans and sub-surface seepage. The term groundwater refers to that which is stored in the pore spaces of soils and rocks; reservoirs of deep sub-surface groundwater are referred to as aquifers. Natural loss of water from these environments is through springs and gradual seepage into the oceans. Replenishment comes from seepage from surface water (see Chapter 1).

Water abstraction, or extraction, is the process by which water is obtained from these sources. The availability of freshwater is threatened by three dominant mechanisms; unsustainable use (i.e. over-extraction); pollution (making it non-potable); and climate change (changes in precipitation).

Water stress is an important measure for evaluating the sustainability of water supplies. It occurs when demand for water exceeds the available amount during a given period of time or when low quality restricts its use. Currently, a country is said to be experiencing water stress if its annual water supply drops to levels below 1,700 cubic meters per person. Water scarcity occurs if the levels drop further to less than 1,000 cubic meters per person.

The World Health Organisation (WHO) has established a set of standards for drinking water (or 'potable water').[1] Water quality can be measured in a large number of ways, including conductivity (salinity), dissolved oxygen, pH, colour, total suspended solids, chemical oxygen demand, biochemical oxygen demand, microorganisms (such as *E. coli*), nutrients (nitrates, phosphates etc.), dissolved metals and organics, temperature and pesticides.

Human activity is a key contributor to water pollution and hence to water quality. Deleterious human inputs into the water cycle include organic chemicals, nutrients, heavy metals, endocrine disruptors, persistent organic pollutants (POPs), pesticides, herbicides, pharmaceuticals, veterinary compounds, personal care products and nanomaterials. Our understanding of the fate and effect of these chemicals and their degradation products varies hugely (see Chapter 5).

Human and environmental health suffers if water quality is poor or water is unavailable. Water scarcity for crop production is a key threat to human health and technologies to reduce the water intensity of agriculture are vital. Excess water brings additional problems in the form of flooding. Water borne diseases and chemical contamination of water have direct effects on human health, the former is particularly prevalent in developing countries (see Chapter 6).

Water monitoring is key to measuring and understanding the chemical and biological quality of water and for taking reactive remedial action. Additionally, fit for purpose advanced monitoring technologies and strategies mean that proactive measures can be implemented to improve water quality (see Chapter 4).

Treatment of water to deliver or return it in a satisfactory condition has traditionally been carried out by a combination of physical, chemical and biological processes. Emerging contaminants, such as pharmaceuticals and nanomaterials, require different approaches and technologies for water treatment. Water treatment is also an energy intensive process and there is significant opportunity for the development of less energy intensive technologies and processes (see Chapter 3).

What is sustainable water management?

In 1995 Dr Peter H. Gleick of the Pacific Institute for Studies in Development, Environment and Security,[2] provided the following definition for sustainable water use: "*The use of water that supports the ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depend on it.*"

Sustainable development is the endeavour to do 'better' than we have in the past: do more with less. On the one side, we seek to be more successful in delivering against our objectives, which are different forms of justice including inter-generational equity, equality of treatment irrespective of genders, ethnicity, religion and those other factors which have in the past been used to create justifications for inequalities. On the other, we have to make the most efficient use of resources over the long term in order to deliver justice: given our past heavy reliance upon non-renewable, depletable resources this includes a shift towards the replacement of those resources by renewable resources. We can express the problem as being one of maximising output O, justice, relative to resource inputs, I [3]. The three best known means of increasing that ratio of O/I are technology, institutions and skills.

Historically, in productivity terms, improvements in those ratios have shown massive improvements: yields of wheat in the UK have more than quadrupled over the last hundred years[4] and most of that improvement has been the result of improvements in the understanding of plant nutrients and the ability to make the appropriate balance of nutrients available to crops[5]. At the same time, the energy requirements to produce one tonne of nitrogen as fertiliser have fallen by approximately 98%. Similar dramatic efficiency gains are seen elsewhere in terms of the energy and water required to produce one tonne of steel and across other technologies. Delivering justice to the population of the world when the consumption of the developed world already consumes more than the global capacity[6] will require both further enhancements in technological capacity as well as shifts to sustainable consumption on the part of the developed world. Here, we may see the adoption of the Water Closet, as opposed to the competing alternative of the Earth Closet[7], as the biggest disaster in the history of water management. Its adoption increased domestic water consumption by around 50% and then required massive investment in a sewer system to transport the polluted water away. The existence of those sewers made them an obvious and attractive means of disposing all forms of waste, including industrial waste: early sanitation legislation in the UK concentrated upon giving local authorities the power to compel a land user to connect to the local sewer. In turn, the discovery of the consequences of dumping untreated sewage into the nearest water body required the introduction of very expensive wastewater treatment plants. In retrospect, much of the technological development of the water and wastewater industries over the last 150 years may be regarded as an expensive technological dead-end, a dead-end which the developing countries have the opportunity to leap-frog directly to a sustainable system of water management. That system is likely to be characterised by demand management[8] and source control both for runoff[9] and for point sources of pollution, coupled to the reuse and recycling of water[10]. But, these systems may potentially involve a higher risk to health than the prevailing highly centralised system as they rely upon multiple, localised treatment works.

Doing 'better' ultimately depends upon our ability to invent better technological options which capacity is in turn based upon the understanding and use of basic chemical, physical and biological processes. What we can do with any given resource is ultimately determined by the laws of chemistry and physics as expressed through the state of technological knowledge: the ability to substitute copper in some use by a material having similar properties of ductility, high electrical transmission or a high thermal coefficient, depends both upon the discovery of such a material and also upon the means of producing and working that material economically.

Those advances in technology will still run into the fundamental characteristics of water, notably that it is heavy and incompressible. In consequence, water management will always be energy intensive so that historically the preference was to use potential energy in the form of gravity rather than kinetic energy to move water. In some areas of water scarcity, the energy costs of lifting water are already high; it is estimated, for example, that 20% of Jordan's electricity production is used in water management[11]. Even when the energy efficiencies of desalination are driven up towards their theoretical limit[12], it is likely that the energy costs of lifting water will limit the scope for increasing the effective availability of water through desalination. Again, the existence of economies of scale is likely to mean that a switch to decentralised water management will result in increased energy usage and potentially, therefore, make the achievement of a zero carbon economy more difficult to achieve. For example, the largest sustainable housing development in the UK, BedZED, originally treated greywater on site through a 'Living Machine' wetland system. This system has now been abandoned because both the energy and money costs of the system were higher than the conventional sewerage system[13].

A key conditionality for delivering sustainable water management is the recognition that catchments, the environment, society and the economy are all interdependent systems and must be managed as such. This is usually described as Integrated Water Resource Management (IWRM): " … *a process which promotes the co-ordinated management and development of water, land and related resources, in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems*"[14].

Sustainable water management, as a strategy for making more efficient use of water, is generally anticipated to involve a number of technologies (Figure 1), as well as the six strategies for pollution abatement given earlier. These are not panaceas; energy consumption will probably rise as the result of the adoption of these techniques as a result both of a decreased capacity to the use gravity to move water and its replacement by kinetic energy, and as a result of the loss of economies of scale in both pumping and treatment. On the other hand, shifting to sustainable water management in new construction involves low costs. Thus, adopting the 5 star standard in the new code for Sustainable Housing, is estimated to cost £2,645 per property or about 12% of the cost of adopting the measures necessary to meet the energy standards. Meeting the standards for the lower 4 star rating has been calculated as £125, or 1% of the cost of delivering the equivalent energy measures[15].

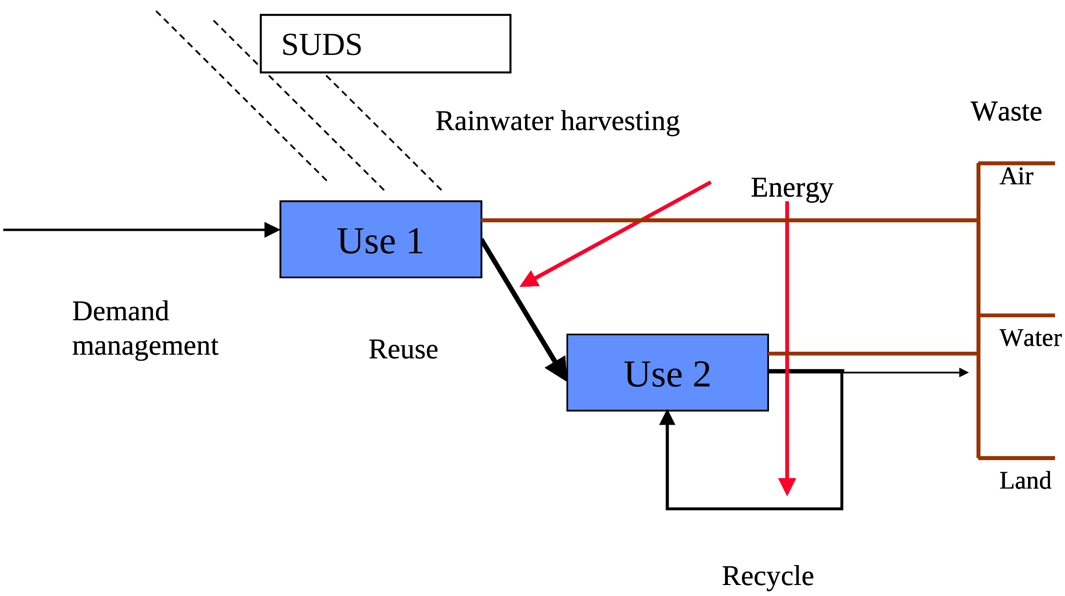

Figure 1: Sustainable water management strategy

Unfortunately, it is not enough to think of catchments as systems; the problem is to manage the catchments as systems. That we have not been very successful so far in our efforts at IWRM[16,17] is a sign of how difficult is this task of integration. This is a task of governance, of which the best known definition is that of the UNDP[18]: "*The exercise of political, economic and administrative authority in the management of a* *country's affairs at all levels. Governance comprises the complex mechanisms, processes, and institutions through which citizens and groups articulate their interests, mediate their differences, and exercise their legal rights and obligations.*"

Governance has two main elements: structures and processes. The structural element is institutions, the systems of rules governing the relationships between individuals and groups[19], where organisations are manifestations of an internal rule structure as well as operating in a wider structure of rules. Those rules may be either informal or social norms, or formalised as laws. Thus, the rule sets and organisations need to be appropriate to deliver integrated water resource management. But integration is, in turn, a response to the increasing complexity of the management problem with which we are faced. In particular, the success of organisations is increasingly measured not by what they do but how successful they are at influencing the behaviour of others; in promoting demand management or SUDS (Sustainable Urban Drainage Systems) rather than at building reservoirs or wastewater treatment works. Consequently, the role of catchment management agencies is being redefined[20].

One specific problem is how to provide financial incentives, a rule set, to water and wastewater companies to promote sustainable water management. What are the incentives for a water supply company to promote demand management, rainwater harvesting, and water reuse and recycling? Equally, what is the incentive for a wastewater company to promote SUDS? This may be a particular problem where the two functions are the responsibilities of separate companies. In this latter case, charges for wastewater collection and treatment for domestic properties and smaller commercial properties are generally levied as a multiplier on to the charge for water supply. If reducing water consumption does not result in a proportional reduction in the costs of collecting and treating wastewater, then the interests of the two companies will diverge. The problem is perhaps particularly acute when the water and wastewater companies are commercial companies. One possible solution is promote the competitive provision of packaged full-cycle water and wastewater treatment to individual sites.

This increasing emphasis on influencing others, where no one organisation has the ability on its own to deliver sustainable water management, places considerable emphasis on the processes of decision making and implementation, and hence on the importance of stakeholder engagement. This raises major questions both as why individuals and groups may find it beneficial to engage in cooperative action and how it may be best achieved[21]. Innovative new processes are being developed under the World Bank's NIPR initiative[22].

Governance is in effect what Aristotle[23] called politics: "*Our own observation tells us that every state is an association of persons formed with a view to some good purpose.*" Similarly, Crick[24] defined politics as "…. *an activity, a sociological activity which has the anthropological function of preserving a community grown too complicated for either tradition alone or purely arbitrary rule to preserve it without the undue use of coercion*". Our problem is to become better at politics both in terms of processes and outcomes; we cannot treat politics as a vulgar practice indulged in by the disreputable. But, as already emphasised, we cannot do better without better knowledge and better technological options. Here, since it is central both to the production of the factors which produce health effects and to the neutralisation of those factors are chemical, physical or biochemical processes, chemistry has to play a central role.

However, a wider problem is that of reconciling advance in theory and its conversion into practice. Scientific advance increasingly takes place on a disciplinary basis; conversely, practical advance requires interdisciplinary working: integrated water resource management requires integrated science. This creates two problems; firstly, the reward structure of academics is disciplinary; and secondly the sheer difficulty of interdisciplinary working[25] (Mansilla et al nd). The speed at which we can resolve these two problems will dictate the speed at which we can deliver sustainable water management.

Sustainable water: the global picture

Global sustainable water and sanitation is well documented in numerous key reports; all reveal a shocking inequality across the globe. The United Nations Children's Fund (UNICEF)[26] estimates that between 1990 and 2004 the global coverage of safe drinking water rose from 78% to 83%. Despite this, the annual number of childhood deaths as a result of unsafe water and basic sanitation still stands at approximately 1.5 million per year.

The United Nations (UN) Millennium Development goals are a set of eight targets established by governments and development agencies around the world that form a blueprint for ethical global development.[27] Target seven, *ensure environmental sustainability,* includes a statement to halve the number of people without sustainable access to drinking water. Many of the other Millennium Goals, however, are inexorably linked to safe and sustainable water supplies, including the aim to reduce childhood mortality rates and to eradicate extreme poverty and hunger.

UN Water, a joint undertaking of the 24 UN agencies, aims to provide up-to-date information on all water related areas, including agriculture, sanitation and resources.[28] In 2003 it published the first World Water Development Report (WWDR), *"Water for People, Water for Life"*, and in 2006 published the second report, *"Water, a shared responsibility"*,[29] an outcome of Phase 2 of the World Water Assessment Programme (WWAP).

The 2nd WWDR attributes the urgent need to address sustainable water as deriving from three key areas:

- Persistent changes in global climates. Lower precipitation and higher evaporation in many parts of the world lead to diminishing water supplies. Increasing environmental pollution damages ecosystems and leads to adverse health effects.
- Major demographic changes are placing a huge burden on water supplies. Rapidly expanding populations in developing countries, mega-cities, towns

and small cities are accompanied by difficulties in establishing infrastructure to provide adequate water supply and sanitation.

- Large changes in the geographic distribution of population places a heavy burden on specific areas of the world. This includes large scale immigration into developed countries as well as movement of refuges in war torn regions.

A number of major water-related disasters have been linked to climate change. These include the Asian tsunami of 2004, heavy flooding of central Europe in 2005, a number of hurricanes in the Caribbean, Pacific and United States throughout 2004-05 and extensive droughts in Niger, Mali, Spain and Portugal.

The World Health Organisation (WHO) and UNICEF further highlighted, within the UN Water report, the connections between health and water. Water related diseases, which provide a measure of the state of water access and sanitation and are particularly wide spread in Sub-Saharan Africa and South Asia, include diarrhoea and malaria amongst many others. Malaria causes illness in 400 million people per year, and 1.3 million die from it; the majority are children under the age of 5. In African countries where malaria is endemic, 30% of out patient visits are related to this disease. The impact of malaria on the African continent was highlighted at the G8 Gleneagles summit in 2006 where funding was promised for treatment and bed nets to prevent the deaths of 600,000 children per year.[30]

The Food and Agriculture Organisation of the United Nations (FAO) and the International Fund for Agriculture Development (IFAD) have highlighted the need for sustainable water supplies with regards to food production and agriculture. Between 2000 and 2030 the production of food crops in developing countries is estimated to rise by 67%, although improvements in productivity should keep water usage increases down to approximately 14%. Currently, although global food security is improving, 13% of the world’s population (850 million people) do not have sufficient access to food.

The United Nation Industrial Development Organisation (UNIDO) has reported in the 2nd UN Water report on the role of water in energy generation. Along with its primary role in hydroelectric power generation, water is used in other schemes such as nuclear-based energy generation. Hydropower is estimated to account for 19% of world energy generation. In Europe 75% of the total potential hydropower generation is being exploited, whereas in Africa only 7% is being used. Although run-of-river electricity generation is highly attractive, there are significant concerns associated with large dam and reservoir construction. Hydropower can play a key role in meeting future energy needs, but in order to retain sustainable water supplies new developments must be carefully designed. Small hydropower projects (SHP) in areas where there are adequate water resources can provide off-grid local electrification, especially in rural areas, without the controversy associated with larger developments.

UNIDO also highlighted the connection between Industry and sustainable water. There is currently rapid economic growth in the Far East and Pacific region, with industry providing 48% of total GDP. Over the four year period from 1998 to 2002, developing nations have experienced an increase in industrial contribution to GDP from 22 to 26%, whereas in wealthy nations it is declining slowly, currently standing at around 29%.

Pollution arising from Industrial activities endangers water resources and damages ecosystems. Industrial development can, however, be decoupled from environmental degradation by the introduction of good environmental governance to reduce natural resource and energy consumption. Such activities are already well established, and include The Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their Disposal, The Stockholm Convention on Persistent Organic Pollutants (POPs) and the EU Water Framework Directive. Zero Effluent Discharge, in which water is recycled and all waste is recovered, should be the aim for all industries. Valuable intermediate steps, however, include cleaner production assessments, transfer of environmentally sound technologies, stream separation, raw material and energy recovery from waste, and optimised waste water treatments.

Sustainable water within the EU

As a direct result of citizen's concerns the European Union (EU) Water Framework Directive (WFD)[31] was adopted in the year 2000 to ensure clean, sustainable water supplies in the EU. Nearly half of the citizens in the EU 25 were worried about water pollution, and in some areas this rose to 71%. The WFD aims to achieve 'good status' for all groundwater, rivers, lakes, coastal and other water bodies throughout Europe. The term 'good status' is based upon the ecological, chemical and physical aspects of bodies of water. As part of the agreement all EU Member States must produce river basin management plans (RBMPs) by 2009, with a set of measures to be met by 2015.

A river basin is defined as the land area from which all water runs into one river. As an example, the Danube river basin covers approximately 8% of Europe. There were about 100 serious floods in Europe between 1998 and 2000, directly affecting 1.5% of Europe's population. There were over 700 fatalities, over 500,000 people were displaced and over €25 billion in insured losses. The 2002 Danube floods caused huge damage over a large portion of the EU, including Germany (damage €230 million), Austria (€232), Czech Republic (€11.7 million), Slovakia (€36.2 million), Hungary (€33 million) and Romania.

The European Environment Agency (EEA) supports sustainable development and improvements to Europe's environment by providing relevant information to public bodies. Its recent report *"The European environment – state and outlook 2005"* included an assessment of Europe's water supplies and needs.[32]

Variation in water supply across Europe is quite marked; Norway, Spain and the UK use more surface water, Austria, Denmark and Germany use more groundwater, and in Southern Europe there is increased use of desalination. Although annual average rainfall on Europe is 3 500 cubic meters, and only 300 cubic meters are withdrawn, regional demand and availability often do not match. Annual freshwater availability in Europe varies from less than 1 000 cubic meters in Cyprus and Malta, 3 000 in France, Italy, Spain and the UK, 10 000 in Austria and Slovenia to more than 75 000 in Norway and Iceland. Cyprus, Italy, Malta and Spain, where water withdrawal is greater than 20% of the total available supply, are considered water stressed.

Water usage across Europe is also highly varied. On average , one third of water abstracted is used in crop irrigation, just under a third in power station cooling tower, a quarter is household use and the remainder is used in manufacturing. In Belgium and Germany, though, over two thirds is used in power station cooling towers, and irrigation consumes less than 10%. In Southern European countries, such as Cyprus, Greece and Malta, irrigation uses 60% of abstracted water. It is worth noting that in Europe, over 80% of irrigation water is either used by crops or evaporates, 80% of manufacturing or household water returns to the environment, but often polluted or in different catchment areas, and 95% of water used in power stations returns almost unaltered.

Future predictions for water supply and usage in Europe remain just as varied as the current picture. In Northern Europe, for example, improved cooling systems in power stations are likely to lead to a decrease in their water consumption. Climate change, of course, will have a significant impact across the whole of Europe; irrigation will consume a further 11 – 20% of abstracted water, unsustainable in many Southern European areas. By 2030, significant areas of Europe will be affected by water stress, including, but not limited to, almost the entirety of Spain, Italy and Turkey, Northern France and areas of Belgium and Holland, and a significant part of the South East and Midlands in the UK. Severe water stress is predicted in Southern Spain, Southern Italy, almost all of Turkey and the South East of England.

Sustainable water in the UK

In the UK the Department for Food, Environment and Rural Affairs' (DEFRA) *"Directing the flow"* report[33] outlines priorities for future water policy and in 2006 the House of Lords Science and Technology Committee reported on Water Management.[34]

The Environment Agency (EA)[35] is responsible for ensuring satisfactory water quality and quantity in England and Wales. It aims to maintain or improve the quality of fresh, marine and underground water and to prevent or reduce the risk of water pollution wherever possible. The EA also works alongside English Nature[36] on the protection of sites of special scientific interest (SSSIs) and Natura 2000 sites. The Scottish Environmental Protection Agency (SEPA)[37] has responsibility for protecting and restoring ground water in Scotland.

Urban diffuse pollution remains a significant problem in the UK. It arises from many activities, such as car washing and maintenance, landscaping and industrial activities. Additional contamination can come from storm drains, sewer overflows and discharges from contaminated land. The nature of urban diffuse pollution means that run-off into, and damage to, water supplies can be very rapid. Damaging pollutants include nutrients, silt, petrochemicals, herbicides, heavy metals, poly-aromatic hydrocarbons (PAHs) and oxygen depleting substances.

Sustainable water concerns are spread across almost all of society and this is indicated in the UK by the Blueprint for Water coalition,[38] whose members include The Association of Rivers Trust, The National Trust, RSPB and WWF-UK. They have proposed a blueprint of ten steps for ensuring sustainable water in the UK based upon the requirements of the Water Framework Directive. The coalition also highlights many water related issues in the UK, including how over abstraction is causing significant damage to spring-fed rivers such as the Mimram, Stour, Wey, Itchen, Avon, Piddle, Tarrant, Kennet and Darrent. There is a drive in the UK to help restore wetlands, and the RSPB and the Environment Agency have restored 275 hectares of Otmoor (Oxfordshire) which had been destroyed by drainage and arable cultivation. Such restoration often leads to an increase in biodiversity, and in this example, a significant increase in the populations of wading birds and wetland invertebrates has been observed.

Although addressed in many cases on a global level, climate change will have a significant impact on water supplies in the UK. In the report *"Climate Change The UK Programme 2006"*[39] some of the impacts that climate change will have on water-related issues in the UK are highlighted, including increased risk of flooding and coastal erosion, increased pressure on drainage systems and summer water shortages and low stream flows.

To achieve sustainable water supplies in the UK requires a number of barriers, both technological and social, to be overcome.

Water usage in the UK stands at an average of 150 litres per day, ranging from 125 litres to 178 litres. In Europe there are several examples of consumers significantly decreasing their consumption. In Denmark *per capita* usage has dropped from 170 to 125 litres per day and in the Czech Republic from 171 to 116 litres per day. Baroness Young of Old Scone, Chief Executive of the Environment Agency, has stated that UK *per capita* daily consumption must drop to 110 litres per day. Measures suggested by the House of Lords Science and Technology Committee with regards to water efficiency include extension of the Energy Saving Trust and Carbon Trust to cover water efficiency, the use of innovative schemes to improve efficiency, the use of water meters and smart billing in households, and an increased development of water efficient appliances and technologies.

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