The Potential Effects of Climate Change and Ozone Depletion on Australian Water Quality, Quantity and Treatability

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ABSTRACT

Water is a resource that is essential for all life on Earth. Presently, this resource and its quality are threatened by an exponentially growing human population as well as unprecedented industrial and technological developments. Climate change and ozone depletion are two major environmental problems facing mankind today. These problems have the potential to further strain currently available freshwater resources. Recent research has shown that climate change and ozone depletion are linked phenomena and their interaction exacerbates current environmental problems. Increased precipitation, surface runoff, solar UV radiation, temperatures, and evaporation are some of the outcomes of climate change and ozone depletion. They impact upon the biogeochemical cycles and aquatic ecosystems in lakes and rivers, and alter the character of natural organic matter (NOM) and, consequently, they have the potential to affect the quality, quantity and treatability of our water resources. As Australia moves towards an uncertain future with the need to mitigate the consequences of climate change and ozone depletion, the issues of changing water quality, quantity and treatability cannot be ignored by governments and water utilities.

KEY WORDS

climate change, ozone depletion, natural organic matter, solar UV radiation, water treatment, water quality

1. Introduction

Freshwater is an essential and dynamic component of the natural environment. Water covers over 70% of the Earth's surface, but less than 1% of this amount is available for human use through catchments such as lakes, rivers, reservoirs and aquifers which are regularly renewed by precipitation driven by the hydrological cycle. Of the remainder, 97% is found in the oceans, and 2% is frozen in glaciers and polar ice caps [1]. Freshwater is a limiting resource in many parts of the world. Presently, 1.1 billion people lack access to safe drinking water supplies, and 2.4 billion people lack basic sanitation services [2]. The future of our water resources will most likely be affected by changes in the environment, technological advancement and population growth. Water resources will become scarcer and more valuable as the world population is expected to increase from 6.5 billion to 9 billion over the next 50 years [3].

There are clear indications that in the next few decades our planet will face global warming and changes in climate not experienced since the end of the last ice age nearly 10,000 years ago [4]. This is considered by most scientists to be due to the rapid increase in atmospheric carbon dioxide (CO_2) over the past 200 years from increased industrial activity. The Earth has warmed by $0.6 \pm 0.2^{o}C$ on average since 1900, and a persistent upward trend over the past 50 years has been witnessed [5]. The Kyoto Protocol was agreed upon in 1997 to limit greenhouse gas emissions for developed nations, but the booming economies of China and India are also likely to contribute to the increasing discharge of greenhouse gases into the future.

Since the late 1970s, the stratospheric ozone layer over Antarctica has been observed to deplete during spring, creating an ozone hole. Present ozone concentrations are approximately half those observed prior to 1970 [6]. With less ozone in the atmosphere, increased ultraviolet (UV) radiation strikes the Earth's surface, causing problems to human health, terrestrial and aquatic ecosystems, and air quality. In recent years, ozone depletion has been detected over the Arctic regions as well. With the signing of the Montreal Protocol in 1987 to phase out ozone depleting gases, a turnaround in stratospheric ozone trends is expected to take place in coming years [7].

Changes in and interaction between the climate and the ozone layer will affect freshwater quantity, quality and treatability (Fig. 1). Climate change will cause a general intensification of the hydrological cycle. Temperature, precipitation, evaporation and runoff are all expected to increase globally, and hydrologic extremes such as floods and droughts will probably be more common and more intense. Ozone in the stratosphere is crucial in shielding the Earth from solar UV radiation, a decrease in stratospheric ozone leads to an increase in solar UVB radiation at the

Earth's surface. These changes in climate and the ozone layer will ultimately affect water resources and aquatic ecosystems through the interactions with natural organic matter (NOM) found in most freshwater resources.

Natural organic matter (NOM) plays a central role in the influence of climatic and ozone changes on freshwater resources. Processes that produce, consume, and transform NOM are important in the overall cycling of carbon, energy and nutrients in aquatic systems. NOM plays a significant role in aquatic food webs, mediates the availability of dissolved nutrients and metals, and modifies the optical properties of water bodies. Ultimately, NOM affects water quality by increasing the disinfectant and coagulant demand in conventional treatment, providing precursor material for disinfection by-products (DBPs), and enhancing biofilm growth in the distribution system. In recent years, extensive research has been conducted on NOM to understand its heterogeneous nature and to develop techniques to minimize its impacts on water quality and treatment [8].

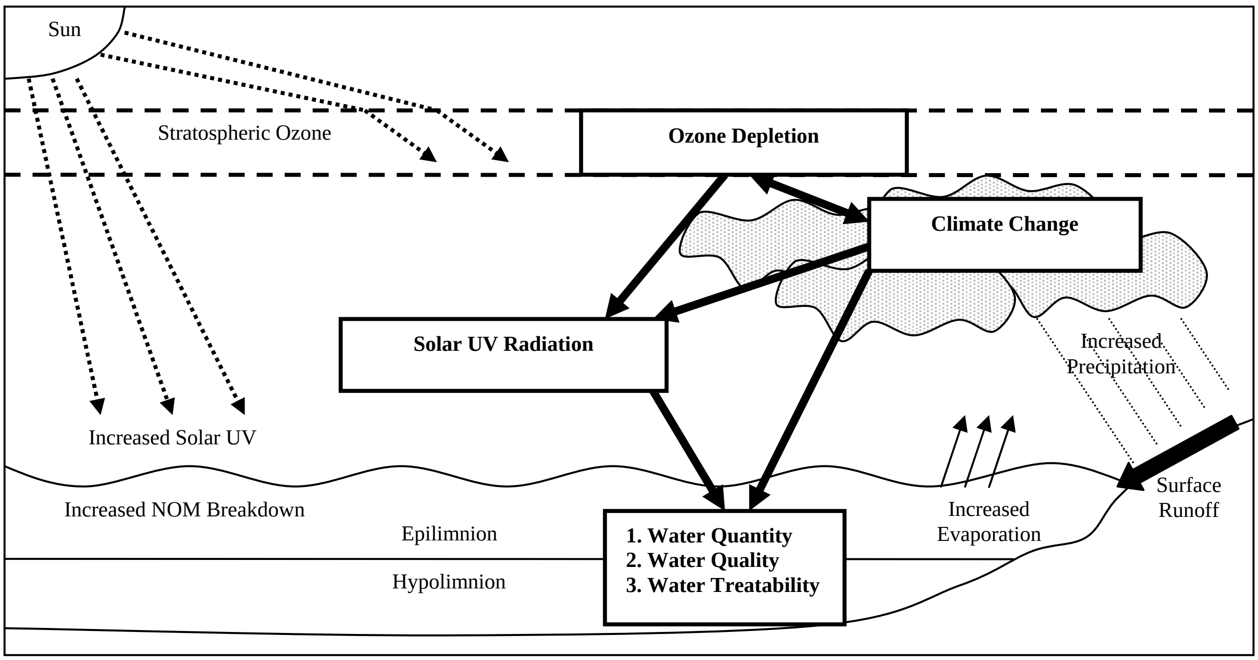

Fig 1. Interaction of climate change and ozone depletion and their effect on water resources

2. Interactions between climate change and ozone depletion

Climate change and ozone depletion appear to be two distinctly different global phenomena. Researchers and governments have set up separate programs to investigate the underlying scientific questions and to coordinate control measures. Climate change is due to a build-up of greenhouse gases that absorb outgoing infrared radiation, while ozone depletion is primarily due to a release of gases that catalytically destroy ozone. Climate change and the effects of greenhouse gases take place predominantly in the troposphere, while ozone depletion and the chemical reactions of ozone depleting compounds take place in the stratosphere.

Recently, increased scientific understanding of both phenomena has led to a growing awareness that important links exist between them [9]. By studying the interactions between the troposphere and stratosphere, researchers have found that the net effect of radiative, dynamic and chemical interactions in the atmosphere results in an intensification of both climate change and ozone depletion and possibly a delay in the recovery of the ozone layer [10]. It may be necessary for scientists and policy-makers to adopt an integrated approach towards the management of the two environmental issues.

Ozone-destroying substances such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are strong greenhouse gases. With their emission, the greenhouse effect is enhanced and the Earth's surface and the lower troposphere become warmer. Ozone is also a greenhouse gas; a loss of stratospheric ozone weakens the natural greenhouse effect in the stratosphere and cools it. A cooling of the stratosphere contributes to the formation of polar stratospheric clouds which provide a medium for chemical reactions that change unreactive chlorine and bromine compounds into more active chemicals that can cause rapid ozone destruction [11].

As greenhouse gases accumulate in the atmosphere, they alter temperature differences between different parts of the globe and different levels of the atmosphere and in this way change atmospheric circulation patterns [12]. These circulation changes may enhance ozone depletion over the poles by weakening some of the warming forces that act on the polar stratosphere. If so, this would have the effect of enhancing ozone depletion over both poles, especially over the Arctic [13].

Tropospheric ozone, a significant greenhouse gas and a major constituent of smog, is photochemically produced. Recent computer modelling indicates that increased UV radiation will result in increased ground level ozone in polluted urban areas where there are high concentrations of nitrogen oxides, carbon monoxide, and hydrocarbons. Highly reactive hydroxyl radicals (•OH) are produced by the photochemical breakdown of ozone in the presence of water vapour. •OH is an atmospheric scavenger that reacts with both ozone depleting and greenhouse gases. Slower removal of these compounds would intensify the process of climate change and slow the recovery of the ozone layer [14].

3. Effects of climate change and ozone depletion on solar UV radiation

The ultraviolet component of solar radiation ranges from 100 to 400 nm and is divided into three bands: UVA (320-400 nm), UVB (280-320 nm) and UVC (100-280 nm). As sunlight passes through the Earth's atmosphere, all UVC and most UVB is absorbed by stratospheric ozone, only approximately 10% of UVB reaches the Earth's surface. UVA comprises most of the UV radiation reaching the Earth's surface. Ozone depletion results in greater amounts of UVB radiation that will have an impact upon terrestrial and aquatic biogeochemical systems. This also has the potential to alter the characteristics of NOM in freshwater systems, influencing the quality and treatability of water.

Ozone changes in the polar regions are more significant than the mid-latitude and tropic regions. Australia receives 12-15% more solar UV radiation compared with similar locations in the northern hemisphere [15]. This is due to its proximity to the ozone hole above Antarctica. Since the 1970s, surface UVB radiation has increased by approximately 6% in the Southern Hemisphere mid-latitudes and by 130% in the Antarctic. A 1% reduction in ozone leads to an increase in UV radiation of 0.2 to 2.0%, depending on the wavelength [16].

The effects of climate change on UV radiation are twofold. The first effect results from interactions between climate change and ozone depletion. The second results from the effect of climate change on other variables such as clouds, aerosols, and snow cover that influence UV directly. A major factor affecting UV radiation received at the Earth's surface is the angle of the sun's rays through the atmosphere, the solar zenith angle (SZA). When the SZA is small, the light path through the stratospheric ozone layer is short, so absorption is minimised. Variability in cloud cover is the second major factor influencing the amount of UV reaching the Earth's surface. The mean attenuation of UVB by clouds is typically in the range of 15-30% [17]. Aerosols can also have a marked effect on the UVB radiation received at the surface, and can attenuate UVB irradiation by up to 50%. Other factors affecting surface UV radiation include seasonal variations, altitude, snow cover and surface reflectivity (albedo).

4. Effects of climate change on Australian water resources

Australia's average temperatures have risen by 0.7°C between 1910 and 2004, most of the increase occurring since 1950. Temperature increases were well spread across continental Australia, and the coastal cities recorded 0.1 – 0.2°C increases per decade [18]. A global average increase of 1.4 to 5.8°C by 2100 (relative to 1990) is expected based on carbon dioxide emission scenarios, the large range is due to uncertainties in the volume of emissions and climate response [5]. Simulations for Australia show that, by 2050, annual average temperatures will rise by 1-1.5°C in the south and 2.5-2.75°C in the north [19].

Recent droughts in Australia have been the culmination of increasing temperatures and highly variable rainfall for the past 50 years [20]. Rainfall projections for Australia show a decrease for the south-western, south-eastern and eastern coasts, with increases in north-western and northern Australia. Wet areas may become wetter and dry areas drier – counter to what water managers and planners would like [18]. Simulations also project the possibility of more frequent heavy rainfall events, but decreased average rainfall, which might lead to associated problems of flooding.

Australia is the driest populated continent and is likely to remain so for the foreseeable future. The combination of decreased rainfall, increased solar radiation and decreased cloud cover result in rapid evaporation and a decrease in water levels in water resources. Australia has a net moisture balance (difference between evaporation and rainfall) deficit [21]. Drying in farming regions will have significant effects on agricultural production and water demand.

Although increases in stream flow are possible in northern Australia due to increased summer rainfall, decreases in stream flow seem likely for southern Australia due to reduced rainfall. Simulations indicate a 25% increase in annual runoff in north-eastern Australia by 2030. Results for south-eastern Australia were not conclusive at ±20%. Tasmania and southern Australia will experience 10% increase and 35% decrease in annual runoff, respectively. In western Australia, annual runoff changes of ±50% are expected [22].

The strongest influence on the fluctuation of Australian climate from year to year is the El Nino-Southern Oscillation (ENSO) [23]. El Nino brings a hotter and drier climate while La Nina brings a cooler and wetter climate. Believed to be linked to climate change, ENSO is usually associated with droughts, floods, heat waves, and other factors that influence agriculture, energy demand, and fire risk. ENSO also affects the frequency of the formation of tropical cyclones in the South Pacific and their likely paths. Since the 1970s, El Nino events have apparently increased and La Nina events have decreased [24].

Regional and recent records have shown an increase in the frequency of tropical cyclones and extreme rainfall events leading to floods [25]. Future changes in frequency will likely be modulated by changes in the ENSO. Climate changes related to global warming may also increase the risk of large-scale bushfires, contributing to the concentration of tropospheric air pollutants and the variety of organic matter constituents found in the surface runoff of fire-affected regions [26].

In Australia and other regions around the world, stratification often occurs in large water bodies during the spring and summer periods. The increased temperatures due to climate change will cause the onset of stratification to be earlier and of overturn to be later, consequently the problems associated with stratified water bodies will become more significant [27]. Problems relating to algal blooms, anoxic water, excessive dissolved metals, foul odour and taste are all related to stratified reservoir waters. Stratified water bodies provide an environment in which cyanobacteria (blue-green algae) may have a competitive advantage over other non-buoyant species of algae. Cyanobacterial blooms are a water quality concern due to the production of algal toxins which have adverse health effects on humans [28].

5. Effects of solar UV radiation on water resources and NOM

Nearly all the energy of biosystems within lakes and streams is derived directly from solar energy and photosynthesis. The energy stored in organic matter formed from photosynthesis is either produced within the lake or stream (autochthonous) in the drainage basin, or brought to the lake or stream in various external sources (allochthonous). Utilization of this energy, and factors that influence the efficiency of conversion of solar energy to potential chemical energy, are fundamental to lake productivity. In addition to these effects, absorption of solar energy and its dissipation as heat have profound effects on the thermal structure, stratification of water masses, and circulation patterns of lakes. Nutrient cycling, distribution of dissolved gases and biota, and behavioural adaptations of organisms are all influenced by the thermal structure and stratification patterns.

The nature and reactivity of the organic matter in a given aquatic system is also dependent on hydrologic conditions which control organic matter residence times and flow paths in soils and sediments. Concentrations of soluble organic molecules are substantial in surface soil solutions and vary significantly between different soil and ecosystem strata, vegetation types, and seasons. Changes in hydrologic conditions associated with storm events, the onset of the rainy season, or the melting of winter snow can result in higher concentrations and compositional changes in the organic matter transported in streams and rivers. NOM transported from the soil into streams under increased flow conditions is often more aromatic and of higher molecular weight than material found in the stream under base flow conditions.

The absorption of solar UV radiation by NOM results in photochemical processes that lead to the partial photolysis of humic macromolecules, with the generation of simple compounds that serve as excellent substrates for bacterial degradation. Transmittance and photolytic activity from UVB and UVA is restricted largely to surface waters, photosynthetically active radiation (PAR, 400-720 nm) in contrast penetrates deeper. Although photolysis of organic compounds is less than that induced by UV in surface waters, the photolytic generation of simple substrates by PAR is significant as well. Photochemical processes are therefore not restricted to the uppermost strata of a few centimetres of aquatic ecosystems, but also occur at greater depths.

The optical properties of lakes and reservoirs are important in regulating photosynthesis and consequently the primary production and ecology within these waters. NOM plays a major role in the attenuation of light in aquatic ecosystems, the decreased levels of PAR may restrict photosynthesis rates in aquatic vegetation. NOM also helps to screen out harmful UV radiation, thus preventing damage to aquatic biota. By trapping high levels of UV energy in the upper layers of the water column, NOM breaks down to more bioavailable organic compounds, minerals and micronutrients. These processes would stimulate bacterial activity in aquatic ecosystems.

Environmental problems such as ozone depletion and climate change influence factors related to the quality and quantity of NOM. Solar UV radiation, stratification and destratification of water resources, changes in allochthonous and autochthonous sources of NOM, all have the potential to alter the characteristics of NOM (Fig. 2). Because the characteristics and concentration of NOM affect several aspects of water quality and water treatment technology, it is a key component in controlling the cost of treatment and the final water quality. Expected changes in the environment due to ozone depletion and climate change will force water utilities to change the way water resources are managed.

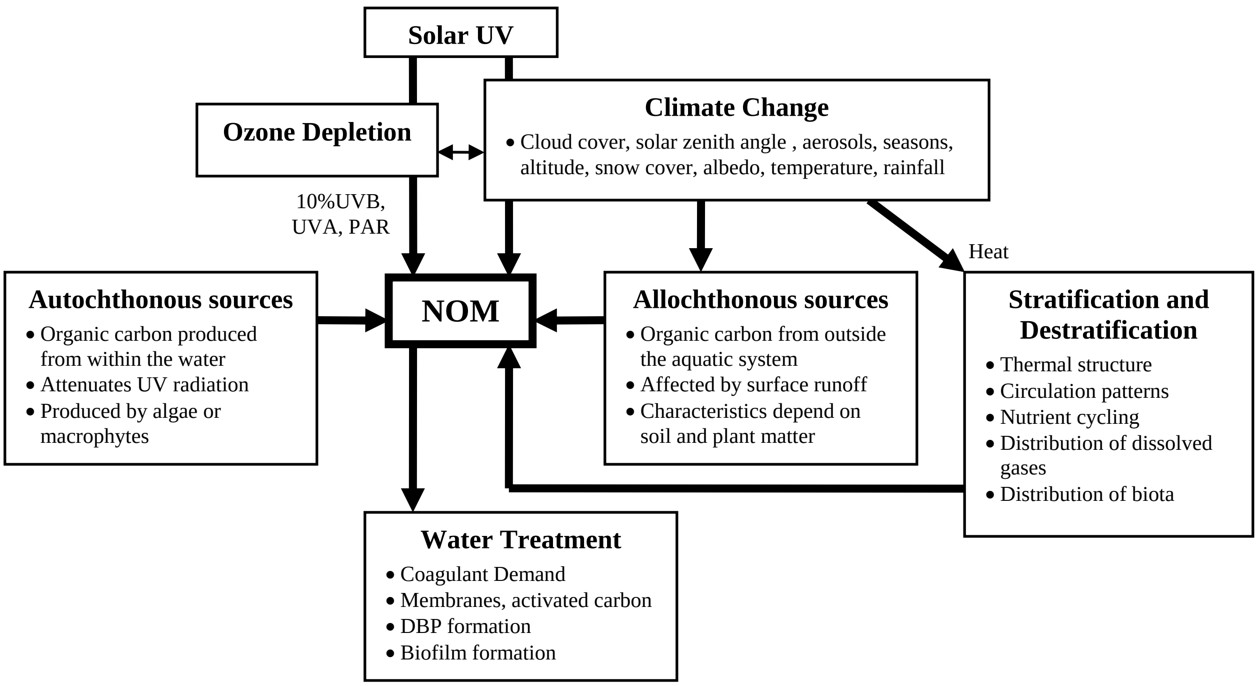

Fig 2. Effects of climate change and ozone depletion on NOM and water treatment

6. The importance of NOM and possible outcomes

NOM is one of the key factors in determining both coagulant and disinfectant dose at water treatment sites. Lowering the concentrations of NOM in raw water should result in a decrease in the amount of coagulant required to treat that water to achieve acceptable potable quality. The reaction between oxidants and the various fractions of NOM can produce DBPs, some of which are known to be harmful to health. Finally, NOM serves as a substrate for bacterial growth. This may lead to growth of pathogenic bacteria in the distribution system where a sufficient disinfectant residual cannot be maintained. Any reduction in the concentration of NOM in our water resources should allow water authorities to reduce water treatment costs, to improve the cost-effectiveness of treatment processes and to meet any future limits on both disinfectant dose and DBP formation.

It is very difficult to predict the overall combined effects of climate change and ozone depletion on NOM, as there are too many interconnecting factors that can result from both phenomena that will affect the characteristics and concentration of NOM in natural water sources (Fig. 2). Current meteorological trends in Australia seem to point toward a hotter and drier climate with increased solar UV radiation in the future. This is reinforced by the interaction between climate change and ozone depletion and the resultant intensification of both phenomena. The quality and quantity of organic matter in surface waters will depend on optical, chemical, biological and hydrological properties of the system and on regional climate [29].

Climate change affects NOM by altering the quality and quantity of NOM loading, and the rates of NOM consumption, production and transformation. The dilution or concentration from exchange of water directly with the atmosphere through precipitation and evaporation is also important. With decreasing rainfall and surface runoff, it is expected that there will be lower allochthonous and higher autochthonous sources of NOM found in freshwater systems. Higher evaporation rates due to increasing temperatures also contribute to the increase in autochthonous NOM concentration. It has been observed that older, more aromatic terrestrially derived NOM will generally have enhanced biological lability following irradiation, whereas recent, algal-driven NOM are generally more refractory [30]. However, it must be noted that the occurrence of unexpected extreme weather events such as storms or bushfires will contribute to sudden surges of allochthonous NOM to the water system.

On the other hand, the depletion of the ozone layer resulting in increased solar UV radiation may result in opposing effects. As mentioned previously, with less precipitation, it is expected that the export of allochthonous NOM from drainage basins will decline. Since NOM acts as the principal attenuator of UV radiation, the declining concentrations of NOM will result in increased solar UV penetration, leading to increased photolysis of the predominantly autochthonous NOM in the water. Compared to the scenario mentioned previously, lakes will become clearer and the mixing zone will deepen for stratified water bodies. Longer water renewal times also mean that there is a greater opportunity for NOM to be photodegraded.

It is very likely for the two contrasting scenarios to balance each other out, with the climate change and ozone depletion induced outcomes keeping the concentration of NOM constant. However, the characteristics of NOM will tend to shift towards autochthonous origin, except for surges in allochthonous NOM during extreme weather events. Due to the chemical heterogeneity of the NOM pool, it may be difficult to determine the specific effects autochthonous and allochthonous NOM will have on water treatment and subsequent water quality. Compared to the effects from increased UV radiation due to stratospheric ozone depletion, climate change related factors seem to have the potential to present a greater impact on NOM quality and quantity.

7. Future expectations and recommendations

Improved water resource management practices are essential to address the increasing demand for water. Impacts of climate change and ozone depletion on water resources will continue to have serious implications for water utility managers in terms of water quality and supply. Energy planning by water utilities will be needed to help reduce greenhouse gas emissions. Water utility managers will need to plan for long-term energy use which will eventually move away from fossil fuels as they become less available; the use of alternatives may increase overall water supply costs. Water utility managers should consider new, improved and flexible engineering designs and operation methods for existing and planned water management systems under a wide range of climatic conditions, using tools such as scenario planning and strategic management. The need for more efficient water treatment practices is likely to become more pressing, as is the need to use alternative sources of water to meet growing future demands.

The need to develop and apply new and alternative water treatment technologies (such as desalination and wastewater recycling) will be without question. The cooperation of water utilities with relevant local and international scientific organizations to facilitate the exchange of information on the latest developments regarding climate change, ozone depletion and their effects on water resources should be encouraged. Public education on these environmental issues will also increase awareness and assist in improving the efficient use of water resources. Finally, governments at all levels should consider legal, technical, and economic approaches for managing water resources in light of the possible impacts of climate change and ozone depletion.

8. Conclusion

As we move into an uncertain future, some things are apparent. Climate change and ozone depletion are global problems that have to be tackled. Even though corrective measures have been planned and are being carried out, improvements to these problems are yet to be seen. These problems are unlikely to be resolved in the near future and so we will live with their lingering impacts on the environment for some time to come. Adding to this is the exponentially growing human population; the consequential demand on water resources will increase to satisfy mankind’s basic and social, cultural, technological and economical needs. The financial and ecological price of water supply for human need is likely to increase in the future. This calls for careful and flexible planning by water utilities and governments to satisfy the projected demand for water. With greater knowledge of the potential impacts of climate change and ozone depletion on precious water resources, the future should be better secured.

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