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THE IMPORTANCE OF WATER SCIENCE IN A WORLD OF RAPID CHANGE: A PREFACE TO THE *TREATISE ON WATER SCIENCE*

The world in which we live is currently undergoing rapid changes, triggered by outstanding advances in natural sciences, medicine, and technology. As a result, the human population grows to levels never known before. Innovative communication and transportation means permit globalization of economy and urban lifestyle. Cities and city life exert an unprecedented pull. More than half of the world's population already live in urban settings – the tendency is rising.

Cities meet the expectations of immigrants, citizens, and businesses only when served by an appropriate infrastructure. Unfortunately, in many parts of the world cities grow faster than the required infrastructure can be planned, financed, and installed. In many cases, installation of water distribution networks and sewer systems, waterworks, and wastewater treatment plants is often lagging far behind schedule – be it because of the lack of financial resources or because higher priority is given to other infrastructural projects, roads, and highways, for instance.

At a larger scale, the water demand of agriculture and industry is growing overproportionally with respect to population size as people shift preference to products requiring particularly high volumes of water during the growth season or during the fabrication process, respectively. Two examples underline this statement – the shift toward meat consumption and the preference of clothing made of cotton fibers. The consumers are often unaware of the water required to raise cattle, swine, and poultry, and to keep cotton fields productive particularly when such fields are located in arid regions as is the case in Uzbekistan, for instance.

Although the water demand is increasing, worldwide, the capacity of local water resources is not. It is even decreasing in very many areas of the world, resulting from pollution of water bodies and soil, from over-abstraction of water, and from effects caused by climate change. Water deficits in municipal, industrial, and agricultural settings are the result.

In many cases, urban and agricultural areas developed in regions where *ab initio* freshwater is scarce. Drought situations caused by global warming and climate change amplify the deficit between water demand and water availability. Over-abstraction of groundwater to meet the local water demand is a common but unsustainable solution to the problem of water shortage. In areas close to the ocean, over-abstraction causes seawater intrusion and subsequent increase of the salinity of groundwater. Rising sea level caused by melting of shelf ice intensifies the intrusion of seawater not only in aquifers but in estuaries as well. In addition, deterioration of ground- and surface water is caused by excess usage of fertilizers and pesticides, and by uncontrolled dumping of solid and liquid wastes onto land. Aggravation of water deficits in municipal, industrial, and agricultural environments is the result.

In the nineteenth and twentieth centuries, health problems and eutrophication caused by pollution of surface- and groundwater were recognized and solved by legal frameworks and enforcement of regulations, and by investing large amounts of money in the development and implementation of infrastructural concepts and technologies. In high-income countries, design engineers and operators of water distribution and sewer systems, water works, and wastewater treatment plants are well trained, nowadays – a major prerequisite of proper functioning of technical installations. In the medium- and low-income countries, however, responsible management of water resources and effective operation and maintenance of water technology are often foreign words.

In the twenty-first century, we are confronted with a comparably much larger and much more complex problem of water management compared to the years past. A new approach to water management and water technology is required in response to the rapid increase at the demand side, and rapid loss of capacity and quality at the supply side. A paradigm shift appears to be urgently necessary.

The old paradigm was the answer to the conditions prevailing in the highly industrialized and water-rich regions of the world. Over the past decades, considerable time was available to develop, implement, and upgrade measures capable of solving the specific local and regional problems. This, however, is not the situation we have to deal with today and in the years to come. In future, we have to support people with effective and robust water and wastewater services even if the capacity of the local water resources is critically short. To avoid evolvement of economic and societal instabilities, we are obliged to develop techniques and management concepts which can be implemented in virtually no time. We have to serve people, industry, and agriculture alike while keeping the function of aquatic and terrestrial ecosystems preserved. We need methods which are adjustable to the changing climatic boundary conditions. We need well-educated water professionals in academia, water services, and water authorities who understand the local environmental, economic, and societal framework conditions, to draw appropriate decisions and take responsible action. We need methods which are financially affordable. These methods are to be safe with respect to public health. Moreover, they must guarantee ecosystems to exert their generic life-supporting function.

The task to solve the complex issue of water-related problems caused by urbanization and lifestyle changes is challenging because of the speed of change at both the demand and the supply side, and also because of the limitations at the financial side. Business as usual is not a tolerable approach.

In the course of a shifting paradigm, we should realize that sectoral approaches (as they were usually taken in the past) are to be overcome. We need to understand that the water quantity and quality issue are inextricably linked to the issue of energy and food supply, and with the issue of land management as well. What we need is a holistic approach. Measures are to be taken which permit solution of the energy, water, and food crisis in conjunction with measures which enable restoration of the self-regulating capacity of terrestrial and aquatic ecosystems in harmony with the human demand for land.

Scientists and engineers are called to take up the task of problem solving as a challenge and as a chance. Solutions have to be found on the basis of the existing portfolio of knowledge and experience, but open minded with respect to the very local conditions in rapid transition. The *Treatise of Water Science* is to be considered as a platform on which innovative research and development may proceed. It summarizes the contemporary state of knowledge in the field of water science and technology and paves the way toward a new horizon. Serving humanity with safe water while keeping the self-regulating capacity of the aquatic ecosystems intact – this has to be our common goal.

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British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Catalog Number: 2010940213

ISBN: 978-0-444-53193-3

For information on all Elsevier publications
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Printed and bound in Italy

07 08 09 10 10 9 8 7 6 5 4 3 2 1

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Editorial: Fiona Geraghty
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TREATISE ON WATER SCIENCE

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VOLUME 1

MANAGEMENT OF WATER RESOURCES

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Preface – Management of Water Resources

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The Greek philosophers gave us a physical world composed of four elements: land, water, fire, and air. Two thousand five hundred years later we are still focused upon these elements, now conventionally referred to as ecosystem (land), water (water), energy (fire), and atmosphere (air), more aware than ever that these elements are essential for all life on Earth. As human populations have multiplied 700-fold since the ancient Greeks, we are facing major crises with each of these elements. At different stages of human development, each has risen to prominence; control of fire was one of humankind's earliest and fundamental scientific discoveries. With fire under control, land took on increased salience, humankind's numbers soared, and we managed to inhabit the entire planet. The other two elements, air and water, were always essential; however, until recently, they were considered so abundant that we would never have to worry about depleting them. However, by the end of the nineteenth century when the globe's land frontiers were closing and filling in, it was then that we as a species began to notice problems with having contaminated the air and water and that it was becoming difficult to find clean air to breathe safely and unpolluted water to drink. In addition, by the end of the twentieth century we discovered that our profligate use of fossil-fuel energy was in danger of changing the atmosphere in ways that were threatening the survival of our species by causing global warming. We find ourselves now on the threshold of the twenty-first century struggling to survive as a species. As a result, the two most salient global issues now facing humankind are energy and water. How do we manage our survival transition into the twenty-first century and beyond?

The intertwined developing resources crises lead us to three critical questions pertaining to the global water situation:

1. *Will we have enough water to grow food to feed ourselves in the twenty-first century?* By far the largest quantities of freshwater are, and will be, those used in agriculture. Currently, agriculture uses about 4000 km^3 of freshwater each year to feed approximately 7 billion people. Even though population growth has slowed down globally, we will still face a population of 9 billion by 2050. The demand for agricultural water is complicated by the fact that as people become wealthier their dietary tastes change, moving away from grains toward animal products. The same amount of water that provided food for 10 people subsisting on grains previously now only satisfies the agricultural needs of one person who has moved up the food chain toward animal products.
2. *How will we provide water and sanitation for an additional 3 billion urban dwellers?* Since 2007 the urban population has exceeded the rural population. This has major implications for sustaining the water and sanitation for cities. For example, China's urban population is expected to reach 1 billion by 2030. Urbanites typically are wealthier than their rural compatriots, and have radically different water demands, more appliances, washing machines, bathtubs, showers, and flush toilets. Even though the absolute magnitude of their demands is much smaller than the demand of agriculture, water plays an important role in urban public health which cannot be ignored. This is particularly the case in the large cities of Asia and Africa where already there are huge unserved populations demanding water and sanitation services. One study estimates that as much as $22 trillion is needed by 2030 just to meet the demands for water and sanitation services.
3. *How should we address the future climate uncertainties?* One issue that water engineers always prided themselves on was that they could make robust forecasts of the future, at least good enough to be able to build reservoirs, dams, and embankments that would function well enough under a wide range of actual future outcomes. The very existence of the possibility of climate change seriously challenges our ability to rely upon our forecasts. The shift from using stationary time series as the basis for future forecasting is seriously undermined when faced with the possibility of nonstationarity in the time series. There is a need for creative adaptation strategies that would help avoid rapid collapse of engineered and social systems.

This first volume of the *Treatise on Water Science* has 11 chapters dealing with how to address these questions. It is about managing our water resources and will, hence, focus on water. Without water, life, as we know it, would disappear from the planet. Water plays an extremely important role in maintaining a sustainable life on this planet for all species including *Homo sapiens*. Only those few exotic species that have managed to survive in environments which do not require potable water would survive. We fool ourselves, however, if we focus only on water and ignore the connections of water to the overall use of global resources because each of them has a critical role to play in supporting human life on planet Earth. This is the major concern of modern studies of water resources.

1 The Water Crisis

Since 1900 the world's population has tripled, but its water demand has risen sixfold (FAO, 2009). These two facts have forced the global community to focus on the management of global water resources. The major emphasis has been on making integrated water resources management (IWRM) a reality (Global Water Partnership, 2000). This is the global water crisis whose dimensions are daily beginning to manifest themselves to international agencies, national and local governments, and particularly to individual citizens. Unlike the fear of using up energy, which has occurred very rapidly, sometimes seemingly almost overnight as with the 2007 and early 2008 petroleum price rises, the water crisis is a slower crisis – but a crisis nevertheless. The situation changes imperceptibly from day to day – we do not see doubling of prices over periods of months, but like melting glaciers, it is an inexorable slow burn toward scarcity. The time frame is years rather than months, but every day there are more of us, each making demands on this global resource. Although we can find replacements for fossil fuels to power our cars and heat our homes, there is no alternative to replace water.

For most important water uses, such as irrigation and drinking water, there is no substitute. Water, however, is influenced by geophysical and geochemical processes which are highly influenced by climatic change on both the supply and demand sides. On the supply side, drying up lakes and melting glaciers can reduce water availability locally, and on the demand side increased temperatures will increase demands for irrigation of food crops, air conditioning, etc. All of these changes will have to be dealt with under a fairly constant global supply of water. The great irony here is that fossil fuels are usually described as nonrenewable resources – they have a fixed amount and could be exhausted – whereas water is a renewable resource of an essentially fixed amount and is used by everybody on the globe, and cannot be used up in the sense that petroleum can be because it is a renewable resource, but access to it by growing populations overtaxes its availability.

2 Why Studying Water Is So Important

Water resources have been studied for millennia. Starting even before the ancient Greek philosophers, Plato (428–348 BC), Aristotle (384–322 BC), and Archimedes (287–212 BC), the Egyptians and the Assyrians had planned, designed, and built major water resource infrastructures throughout the Middle East. The Romans took the Greek concerns about water and public health and expanded them up to a global scale throughout the Roman Empire. The city of Rome with its 16 major aqueducts was a marvel of both engineering and water management, with a per capita water availability equivalent to current European standards. Over the succeeding centuries, we have theorized, analyzed, and prioritized water in myriad ways. The great scientists and engineers from Renaissance Europe through the end of the nineteenth century, Galileo (AD 1564–1642), da Vinci (AD 1452–1519), Torricelli (AD 1608–47), Pascal (AD 1623–62), Daniel Bernoulli (AD 1700–82), and Darcy (AD 1803–58), just to mention a few of the major contributors, made major breakthroughs which still govern management of water in all its forms today.

3 Current Global Water Balance

The International Water Management Institute (IWMI), located in Sri Lanka, has adopted the blue–green water paradigm suggested by Falkenmark and Rockström (2004), in which the water accounting is done according to whether it is due to evaporation (coded green) or due to the residual surface and groundwater runoff (coded blue). Of the total annual terrestrial rainfall, called the renewable freshwater resources, of 110 000 km^3, 56% evaporates by biological processes, forest products, grazing land, and biodiversity; 4.5% is evaporated from rainfed agriculture (crops and livestock); a further 0.6% of the green water is evaporated from irrigated agriculture along with 1.4% from runoff sources (these are called blue water); and an additional 1.3% is evaporated from open water storages from man-made reservoirs and lakes. Cities and industry demand only 0.1% of the total and 36% returns to the ocean. The 110 000 km^3 of precipitation on the terrestrial landscape is extremely small in comparison with the total resource base and the amounts evaporated in producing food and fiber. Of course, it should be recalled that the actual withdrawal of water from the ecosystem for cities and industries could be several times larger, but that about 85% of these uses (albeit contaminated) return to the runoff account of the terrestrial system. These issues are explored in greater detail in Volume II of this treatise.

4 Establishing Water Policy

It is a commonplace fact that if a resource has little or no value then it will be overused. Therefore, one of the major issues in water resources planning and management is to identify the value of water. The value of water has been pondered by scholars for millennia. Plato observed that "only what is rare is valuable, and water which is the best of all things … is also the cheapest, as quoted by Hanemann (2006) based on Bowley (1973) from Plato's *Euthydemus*. Two thousand years later, in considering the difference between the market price of commodities and their economic value, the eighteenth-century economist Adam Smith compared the value of diamonds and the value of water. In his book *The Wealth of Nations* (1776), Smith made the distinction between value in use and value in exchange. Water, which has great value in use, often has little value in exchange, whereas diamonds, which have little value in use, have enormous value in exchange. Both Plato and Smith pointed out that the market price of an item did not always represent its true value. In order to predict water demand how we value and price water is very important.

5 Predicting Future Demands for Water

Predicting future demands for any resource is fraught with difficulties, but the complexity of water and its singular issue of finiteness make it particularly difficult to forecast. For example, how much should we worry about climate change and global warming? Global warming – one of the great scientific debates of the twentieth century – has now the opportunity to become the political debate of the twenty-first century. A few scientists in the nineteenth century warned of the effect on the atmosphere of excessive release of carbon dioxide into the atmosphere due to the burning of fossil (carbon-based) fuels. It was not, however, until the 1950s that serious comprehensive CO_2 measurements were made. Since then large amounts of research funds have been expended in the field of climate science. Ultimately, in 1990, the United Nations established the Intergovernmental Panel on Climate Change (IPCC). The IPCC has produced four assessment reports so far dealing with the effects of changing greenhouse gas concentrations in the atmosphere. The IPCC has been incredibly successful in raising the status of the scientific understanding of climate change. The action in the United Nations (UN), however, has now shifted away from scientific research toward political action which will promote mitigation and adaptation strategies that could seriously curtail the increase of CO_2 in the atmosphere by the end of the twenty-first century.

In its Fourth Assessment Report in 2007, the IPCC identified five key impacts of increasing global average temperature: water, ecosystems, food, coasts, and health. A closer reading of the text shows that many of the most serious impacts on the nonwater areas are, in fact, mediated via water. Therefore, for instance, impacts on food are largely due to hydrological changes; aridity has major impacts on food, ecosystems, and human health. Thinking about the relative issues involved in climate change, Mike Mueller (2007) of the Global Water Partnership (GWP) said, "if it's *mitigation* then the focus is rightfully energy, and if it's *adaptation*, it will be water resources!" By this, he implied that the bulk of the mitigation strategies deal with handling the use, and development, of new energy resources, and the adaptation strategies will be mostly driven by water concerns. Hence, we need to focus on the water-adaptation strategies, bearing in mind that adaptation for other sectors may include many of the same, or similar, strategies. The pivotal role of water impacts, and hence water's importance to adaptation, is also stressed in the Stern Review (2006).

The local and regional effects on water however are inconsistent among the climate models, often predicting large regional differences in magnitude, variability, and direction of change for the most important hydrology parameter, the precipitation. However, whichever of these models one endorses, there is still a question as to what to do in meeting the future water demands. If we are interested in adaptation to global warming and climate change, it is largely irrelevant which of the models we accept, because operationally there will be small differences among the adaptation strategies that one should follow, but major differences would arise if we were following a mitigation strategy. Surprisingly, even accepting the most conservative scenario leaves one in a strikingly similar situation – how to plan for the future under highly uncertain outcomes. The issue boils down to how do we deal with uncertainty in making decisions about water planning and management? Water engineers and hydrologists are supposedly expert at making such forecasts in a very uncertain world.

Much of the focus has been on changes in the physical parameters, such as precipitation, stream flows, and evaporation, but rising global populations, coupled with rising incomes, and a concomitant increase in per capita consumption, will inexorably lead to serious consequences for the water resources in many areas of the globe, regardless of what happens to climate change. It is the old Malthusian population/resources debate from the early 1960s; only now we have India and China moving into the middle classes in a big way. Keyfitz (1976) pointed out many years ago that it is the increasing middle class and their consumption patterns that were going to be the major problem for environmental sustainability. How we can adapt to meet these demands will be the major struggle for the remainder of this century.

In planning for the future, we must also be aware of unintended consequences of our actions. One example of this is the current US attempt to mitigate climate change by reducing consumption of carbon-based fossil liquid fuels. During 2007–08, fueled by record crude oil prices, we rushed headlong toward a biomass-based liquid-fuel cycle. Because of their huge demand for cropland, water, and agricultural chemicals, the widespread development of biomass fuels turned out to be a disaster for the poor people of the world whose food budgets could not compete with the middle classes' love affair with their automobiles. This means that water planners and managers need to worry a great deal about climate change. The consequences of the climate change will become apparent only if the planners work within a holistic framework to ensure that all of the consequences of climate change can manifest themselves.

6 Drivers of Socioeconomic Growth

Among the earliest modern commentators on the drivers of socioeconomic growth and decline were Adam Smith, Edward Gibbon, Thomas Malthus, David Ricardo, and Karl Marx. Adam Smith, a Scottish economist, published his *Wealth of Nations* in 1776, which became the great classic of capitalist economic thinking. Gibbon, an English historian, combed the history of the Roman Empire for clues for these drivers in his *Decline and Fall of the Roman Empire* (1776–89). Malthus, an English country parson and economist, focused on the relationship between population growth and agricultural productivity in his seminal *Essays on Population* (1798). Ricardo, an English businessman and economist, focused on the declining economic returns from all forms of production and the increasing costs faced by industry over time. Finally, Karl Marx, a German sociologist and progenitor of Marxism, saw growth coming initially from capitalist accumulation and later from the labor of the proletariat.

From their writings we see a concern about running out of resources as long ago as the eighteenth and early nineteenth centuries, well before the sixfold increase in population and 40-fold increase in per capita wealth arrived in the early twenty-first century. Malthus and Ricardo were particularly prescient about the roles of population, food, and energy resources. Malthus postulated a geometric rate of growth (like compound interest on a bank deposit) of population and an arithmetic growth (simple interest on a bank account) of land being brought under cultivation and, hence, arithmetic rate of growth of food production. Regardless of where they start, these curves will always intersect after a period of a couple of decades, and Malthus predicted widespread famine or violent conflicts to bring food and population into alignment with each other by 'misery, war, pestilence, and vice'. Ricardo articulated 'declining returns' on investments in resources (coal and iron ore in his time; water, oil, and gas in our time) whereby the best (least-cost) resources are used first, followed by the next best, and so on. Increasing demand for the resource leads to price increases that will continue to rise until the resource becomes too expensive to use. These two nineteenth-century concepts can be used to explain our current water resources crisis and suggest pathways to end the crisis.

We see these two concepts at work, for instance, in the case of New Delhi the population growth rate clearly exceeds the rate of possible increase in the water supplies (Malthus). On the other hand, in suburban Los Angeles (LA) as the cheapest sources of water are fully exploited, we see the Ricardo effect of increasing costs at work. When LA was developing in the 1930s, water was available at a reasonable cost, but as more and more people demanded more water the cost of supply was also increasing (the best projects had already been built). Without any technical breakthroughs, this means that the cost per unit of water keeps on increasing as time goes by.

Of course, these constraints were also at work over previous centuries, even before they were articulated by Malthus and Ricardo, but *Homo sapiens* were able to avoid them by expanding our resource base through annexation and colonization, to bring in cheaper resources and food; by finding substitutes for scarce resources; and by improving our technology so that the same amounts of land and resources could be used more efficiently. Examples of these effects are seen in the British response to its nineteenth-century rapid population increases. More food was produced, not in England with its limited land and climate resources, but by Australia and other colonies such as Canada and India. This meant that the agricultural land was no longer a constraint on feeding the increasing population. So, Malthus' limits and Ricardo's increasing costs were avoided for the time being; however, since the globe is now pretty much filled up and most of the easiest available water is in use, there are few opportunities to expand the physical supply. The only option available to us now is improving the efficiency of water-use technology, but this is where we run into Ricardo's increasing cost problem. The real question facing the globe at the start of the twenty-first century is whether we can keep on improving our technologies, or finding cheaper supplies or substitutes. However, just because these adaptations worked well over the past 200 years does not mean that they will necessarily continue to work. This is the crux of the problem facing global water resources.

7 Transboundary Conflicts

In historical times, control of water was the source of major conflicts among users often leading to skirmishes and minor wars. Peter Gleick (2009) tracked the history of water conflicts from 3000 BC to AD 2009. Historically, these have ranged from minor to major conflicts, but in recent times since the 1940s there has been less direct conflict and more attempts to resolve water issues by negotiation. He wrote, "There has been a lot of discussion about 'water wars,' a term that sounds great, but to which I do not subscribe: wars start and are fought for many reasons and while water has often been a target, tool, or objective of violence, it is certainly hard to ascribe the primary reason for any war to water alone" (Peter Gleick, 2009).

However, the lack of availability and access to water may have been one of the conditions leading to many wars. The lack of access to water can have major impacts on the health and wealth of nations; major occupations, such as fishing and farming, cannot flourish, and the growth of cities will be limited. With the development of nation-states in the sixteenth and seventeenth centuries, the lack of access by downstream users and the control by the upstream populace was firmly established. This meant that, without a treaty, the downstream users were essentially cut off from use of the flowing river. The Industrial Revolution brought serious pollution to the rivers which also impacted the downstream users.

The UN's International Law Commission spent 26 years from 1971 to 1997 drafting the UN *Convention on the Law of the Non-Navigational Uses of International Watercourses* (1997). As of 2010, it has not yet been ratified by the UN General Assembly by the requisite 35 countries needed for it to come into force. The existence of such a treaty is a good indication of the international community's intentions to improve the nature of collaboration among the riparians in international and transboundary rivers; however, the inability to ratify the Convention says a great deal about the wishes of upstream countries not to cede sovereignty to a supranational body. Despite the nonexistence of a clear set of laws and treaties, customary international laws have used many principles such as prior consultation, avoidance of significant injury, equitable apportionment, nondiscrimination and nonexclusion, and provision for settlement of disputes embedded in the UN treaty. Moreover, the fact that it has not yet come into force has not hindered the resolution of many smaller water conflicts relying on the common-sense ideas presented above. Moreover, even when ratified, the Convention lacks an effective enforcement mechanism and will thus still rely largely upon the goodwill of upstream parties, or the hegemonic strength of the downstream countries.

Water conflicts seem to arise every time a river crosses a boundary. For instance, in the Colorado Basin, despite the existence of the Federal Interstate Colorado Compact, there are still serious water conflicts among the seven US basin states and Mexico. In India, we see similar conflicts regarding the Ganges River, both domestically and internationally, with Nepal and Bangladesh sharing access. Transboundary water conflict is one area in which the conflicts among the parties really emphasize the need for clear and transparent rules for cooperation.

The present seems to be one of the periods of great interest in international rivers, as experts estimate that there are over 145 countries with at least participation in one or more of the 261 international river basins on the Earth. Over time, there have been as many as 300 river-sharing agreements in Europe since the Treaty of Versailles in 1815. However, almost all of these treaties dealt with regulating in-stream use for navigation, hydropower, fishing, and pollution disposal, all of which did not involve the large-scale diversions of water which now regularly occur with irrigation developments. Large withdrawals typically create very difficult water-allocation problems for the downstream countries and, in history, were typically resolved with violence or threats of violence. In our times, we would rather resort to negotiations than war.

The previous period of great concern about transboundary river conflicts was in the 1950s and early 1960s. This period culminated in a successful treaty on the Indus Basin, brokered by the World Bank and signed by India and Pakistan. The accord fueled optimism for resolving other major water conflicts. At that time, basins such as the Ganges–Brahmaputra, the Mekong, and the Nile (and even the tiny Jordan River) were subject to detailed analysis, even to the extent of creating river basin commissions in an attempt to avoid conflict among the parties. Unfortunately, this era of concern came up short. Of these large rivers, only the Indus was eventually successfully developed. Currently, we are experiencing a resurrection of conflict, fueled by the shortage of water caused by rapid development and huge population growth, and possibly global warming.

To allocate – or reallocate – the flows of a river is always a political decision. No matter how detailed the technical, economic, and social studies are, hard choices have to be made among the various users who stand to gain and lose from such accords. This is true whether the river is a national river or crosses international borders. However, transboundary rivers imply a level of political decision making that goes beyond local and national interest groups. It requires the ability to negotiate between sovereign nations.

All rational planners recognize the value of cooperation on river-sharing issues, from sociocultural terms to trade and economic ones. What is not clear, however, is how to put a value on cooperation; in other words, just how valuable is cooperation?

8 River Basin Politics

The problem with purely political decisions is the lack of predictive behavior on which they reside. Thus, many politically inclined decisions have led to a deviation from the scientific–technical-based analysis, which accounts for the quantitative benefits from sharing resources among the coalitions of competing groups. Political considerations are sometimes heavily influenced by noneconomic factors outside the technical analysis. They are often pursued separately and apart from economic objectives, with different personnel and rituals. Political approaches tend to be more descriptive and idiosyncratic than the analogous models in the sciences. Ultimately, foreign policy is the most influential determinant of a country's position on international rivers. Linkage of the river settlement to other outstanding economic and social issues between and among countries is important, as is achieving reciprocity for one's actions either in the linkage of issues or in sharing benefits that are only achievable through international cooperation. In addition, the climate for agreement is a prime political basis for sharing water resources; this comes about when countries have common or shared technical perception of the problems, networking and contacts at the transgovernmental levels, and the need to be seen as being collaborative as a nation.

A wide range of solutions are possible in most negotiations, while the net benefits are not the only consideration; many political issues dominate in shaping the decisions on the locations of the investments which might not necessarily be in the interest of the best technical planning.

Managing common property resources is a very difficult endeavor, and the added complexities of transboundary water are no exception. An interesting phenomenon is that river flows have both negative and positive externalities typically working only in one direction, that is, downstream. This pervasive unidirectional feature of water use means that resolution of basin conflicts through mutual control of external effects that work reciprocally is generally ruled out. However, downstream countries can also benefit from some positive external effects of upstream use. Aside from the water allocation problems that arise from the physical sharing of a common resource, there are also many water-quality problems that can arise downstream as an effect of upstream use. Natural processes such as floods and droughts can also cause major downstream effects and are sometimes mistaken for man-made externalities, and thus lead to further mistrust and tensions among the riparian states.

9 The Contents of Volume I

In presenting a discussion on water resources, this volume has been constrained by the width of the definitions of what constitutes the field. We have presented just 11 chapters which while they cover a broad range of concerns, they do not, by any means, cover the full range of concerns. We do, however, present materials dealing with the three questions outlined at the start of this chapter: feeding the global population, providing water supply and sanitation to the ever-increasing population, and some approaches to dealing with the huge uncertainties associated with potential global climate change.

The first three chapters deal with the broad frameworks of IWRM, governance, and water as an economic good. The chapters attempt to lay the groundwork for dealing with water as a fundamental resource for development. In Chapter 1, Roberto Lenton explores the history and evolution of the concept of IWRM and reports on various assessments and critiques of the concept. In particular, the critics have focused on definitions that tend to be narrowly focused such as a country having a national water policy, or a water law, or the river basin as the focus of planning, or participatory management. Lenton also provides a set of criteria by which IWRM could be viewed in practice. These are a sensible set of criteria and if followed would make a major difference in the sustainability of water-sector decisions. In Chapter 2, Edella Schlager takes up the issues of water governance. She emphasizes a bottom-up approach working from the water users up through multiple layers of governance. She emphasizes the fact that the modern approaches to water development and management are mostly based on methodology developed by experts for experts. She claims that the challenge now is to design and fit water governance organizations into complex multiscale and intergovernmental and watershed systems. It is no longer a game for experts controlled and run by experts. In Chapter 3, John Briscoe deals with how to value water in its different uses. His major split is between urban water and water used for irrigation, or the use of water as urban infrastructure and public health and water in its productive mode for food production. In both cases, he describes how to evaluate the direct and indirect benefits associated with water use. He argues that the indirect benefits associated with water use can be as large as, or larger than, the conventionally measured direct benefits. He concludes with an appeal to move away from the conventional formulaic applications of benefit/cost analysis and attempt to identify critical supplementary investments to use more fully the multiplier effects of large infrastructure projects.

The next three chapters deal with the practical socioeconomic issues of forecasting the demand for water, the pricing of water and sanitation services, and how to know if interventions in water supply really have the benefits attributed to them. In Chapter 4, Benedykt Dziegielewski and Duanne Baumann point out that credible long-term forecasts of water demand are essential to planning for the long-lived water infrastructure. They show that such forecasts must be based on a high level of disaggregation of demand; the uses of econometric models grounded in economic theories of production and consumption, considerations of potential climate change, and must, above all, provide explicit and plausible assumptions. Dale Whittington in Chapter 5 reviews the role of economic pricing approaches to managing water and sanitation services. In this chapter, he cautions against some of the enthusiasm for investments in social overhead capital expressed by Briscoe in Chapter 4, with the potential for over-subsidization of large projects at the expense of smaller ones. Following up on this theme, Alix Zwane and Michael Kremer, in Chapter 6, examine the evidence whether community-level rural water infrastructure successfully reduces diarrheal disease and conclude that the evidence does not support it. However, from their review of the literature they found evidence that sanitation and hygiene are more important than water quality.

The next set of three chapters cover the role of groundwater in providing water resources for many different types of water services, managing water for agriculture, and managing the aquatic ecosystem to provide adequate protection of the environment. In Chapter 7, Lopez-Gunn, Llamas, Garrido, and Sanz assess the development of groundwater over the past half century. They very broadly review the assessment of the total resource available, the economics of groundwater use, institutions and governance of groundwater, and the future sustainability of the resource. They conclude that groundwater may be the most important water source under the more extreme climate-change scenarios, in particular for irrigation in low-latitude countries. They stress the need for better governance structures for groundwater management and that much higher level of user participation will be required fo sustainable use of the resource. In Chapter 8, Jorge Ramirez Vallejo makes a comprehensive review of all aspects of managing water for agriculture and concludes that the majo challenge in this area is to reverse the serious failure of institutional arrangements at the national and local levels to dea with water correctly. The concluding chapter in this section b Max Findlayson on managing aquatic ecosystems recognize the interdependence of people and their environment an focuses on the management of water to support the ecosysten and the environment. He concludes with a strong support fo the Millennium Ecosystem Assessment as the best approach t managing wetlands and their aquatic systems. He points to th need in the coming decades to address the trade-offs amon current and future uses of wetland resources, importantly in between agricultural production and aquatic diversity.

The final two chapters return to some political and socia issues of water resources management. In Chapter 10, Davi Moreau reviews the problems with implementing ambiguou water policy. He uses the case of the experience in the US o implementing the Clean Water Act especially under the federa system where the states are left to implement national polic He shows how there are few ambiguities in dealing with poin sources of pollution, but many in dealing with nonpoin sources which has led to the Balkanization of the implementation with the individual states essentially ignoring downstream states when setting goals for total maximum dail loads (TMDLs). Fittingly, the volume concludes with a chapte by Casey Brown on risk assessment, risk management in th context of potential climate change. He develops an approac to risk management that attempts to reconcile traditiona approaches with our growing knowledge of uncertainty tha mark the hydrologic records. He concludes that the wate community has focused primarily on the means to reduce th uncertainty related to hydrologic events, but little effort ha been devoted to reducing hydrologic risk to society or t communicate risk to promote risk-reducing behavior.

Acknowledgments

The editor wishes to thank the following persons who helpe in the review of the manuscripts in Volume 1: Chris Bassc John Briscoe, Robert Brumbaugh, Ximing Cai, Torkil Jonch Clausen, Line Gordon, Chuck Howe, Annette Huber-Le Roberto Lenton, Tom Maddock, Suzanne Ogden, Margare Owens, Cliff Russell, Mike Shapiro, and Richard Vogel.

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VOLUME 2

THE SCIENCE OF HYDROLOGY

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Preface – The Science of Hydrology

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The world is changing and it seems that the speed of changes is accelerating. In the overall introduction of the *Treatise on Water Sciences,* the editor-in-chief Peter Wilderer (The Importance of Water Science in a World of Rapid Change: A Preface to the Treatise on Water Science) discusses the prevailing changes, its drivers, and possible impacts on different water disciplines. A major challenge is that all changes and their various impacts are interacting with each other, although how and to what extent is often poorly understood. For scientists and practitioners, this makes the problem identification and the development of sustainable solutions for water problems a very difficult task. Therefore, it is very timely to summarize the contemporary state of the knowledge in the different fields of water sciences and technology, and to provide a platform for innovative research and development. I am pleased to conclude that this volume on hydrology is an important piece of the complex puzzle.

What is hydrology? The International Association of Hydrological Sciences (IAHS) in collaboration with UNESCO defined hydrology as the "science that deals with the water of the earth, their occurrence, circulation and distribution, their chemical and physical properties, and their reaction with their environment, including their relation to living beings." In addition, it states that hydrology is the "science that deals with the processes governing the depletion and replenishment of the water resources of the land areas of the earth, and various phases of the hydrological cycle." This is indeed a very wide definition. Many aspects of the chemical properties and interactions with the environment are part of Volume 3 of this treatise. Topics that are directly related to the management of the water resources are part of (Preface – Management of Water Resources) of this treatise. However, this volume (The Science of Hydrology) deals with all major components of the water cycle and key water-quality aspects. It also discusses the linkages to closely related disciplines.

The aims of the science of hydrology were well summarized by the Dutch Foresight Committee on Hydrological Science (KNAW, 2005) as follows:

1. to understand the mechanisms and underlying processes of the hydrological cycle and its interactions with the lithosphere, atmosphere, and biosphere;
2. to enhance our knowledge of interactions between the hydrosphere and atmosphere, the hydrosphere and lithosphere, and the hydrosphere and biosphere, thereby increasing our understanding of the role that water plays in the Earth system;
3. to quantify human impact on the past, present, and future conditions of hydrological systems; and
4. to develop strategies for sustainable use and protection of water resources, hydrological systems, and the associated environmental conditions.

The science of hydrology is special, as it holds a place, on the one hand, in the field of Earth System Sciences, where it is directly linked to earth science disciplines, such as atmospheric sciences, geomorphology, geology, soil sciences, geobiology, and ecology. On the other hand, hydrology is an applied science and, as such, a part of engineering. This makes the discipline highly relevant to the management and development of the water resources and the prediction and mitigation of water-related natural hazards (floods, droughts, landslides, etc.) to finally support life, civilization, and sustainable development. These complementary aspects of hydrology (Earth System Sciences and the basis for water management/engineering) make it an exciting and very relevant discipline. It is quite a dynamic discipline given the significant developments of the past decades; many of them are reviewed in this volume.

The volume starts with a comprehensive overview of global hydrology and the spatio-temporal variability of hydrological fluxes and water resources on a large scale. It continues with several chapters on the main variables of the water balance, such as precipitation, evaporation and interception, and stream discharge; then it goes on to discuss the storage components of groundwater, soil water, lakes, and reservoirs. Unfortunately, a chapter on snow and ice, the globally largest and regionally/locally often very important water storage component, was withdrawn at a late stage and could not be replaced in time.

The volume continues with several chapters discussing the state of the art and the possible future developments of observation methods for ground-based techniques (i.e., field-based methods, tracer techniques, and hydrogeophysics) and remote-sensing techniques. Key data analysis and modeling techniques as well as theoretical considerations are reviewed in four, mainly theoretical, chapters on scaling and regionalization, statistical methods, hydrological modeling, and uncertainty estimation techniques. The linkages between hydrology and aquatic ecology and biogeochemistry are discussed in two comprehensive chapters. Two chapters are related to the processes and issues of erosion and sedimentation as well as surface water–groundwater interactions.

The inclusion of all these topics results in a sizable volume with 20 chapters, exceeding 500 pages. However, several hydrology-related topics are not or could be only partly covered (e.g., urban hydrology, snow and ice, coastal hydrological systems, landscape evolution, and hydrogeomorphology). Perhaps this can be seen as an invitation to redo the exercise in a few years from now, and to review the latest developments in this dynamic field and strive for more completeness.

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TREATISE ON WATER SCIENCE

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VOLUME 3

AQUATIC CHEMISTRY AND BIOLOGY

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Preface – Aquatic Chemistry and Biology

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The World of Aquatic Chemistry and Microbiology

Aquatic chemistry and microbiology do not belong to the classical subjects taught in universities. Nevertheless, they are part of many curricula in natural sciences and engineering. It is beyond doubt that the fascination of the molecular dimension of water itself and all its constituents, which goes like a red threat through all the aspects of structure, transport, and reactions of and in aquatic systems, attracts so many people. Due to the broad and fundamental importance of water for life, including the humans, the molecular water sciences (MoWaS) have to be transdisciplinary. The discipline includes not only physics, chemistry, biology, and geology, but also mathematics, engineering, and economics and even parts of social sciences. As a consequence, several subjects have developed based on fundamental ones but focusing on the special aspects of water, examples of which include limnology, oceanography, hydrogeology, hydrology, groundwater dynamics, drinking water treatment, municipal water management, industrial water usage, wastewater treatment, and hydrothermal usage. Many of them either are cross-linked or bridge the gap to the fields of quantitative water management.

The big challenge when dealing with MoWaS can be deduced from the nano- and microscale of the substances involved and their low concentrations. The related bio-response can range from subtle to acute toxic effects. Methods to obtain reliable results are still scarce, especially for applications in natural environment. Here, the influences of matrices and the synergetic or antagonistic effects in multicomponent samples are often unclear.

It is well accepted that water is the fundamental basis for our known life and in its unique function cannot be replaced by anything else. The physical properties of liquid water are reflected in its properties as transport medium, reaction phase, and mediator for higher molecular structures. One of the most impressive properties of the water molecules is the ability to form intermolecular hydrogen (H)-bonds. Linus Pauling once said, "… the hydrogen bond is especially suited to play a part in reactions occurring at normal temperatures, and I believe that it will be found that the significance of the hydrogen bond for physiology is greater than of any other single structural feature." In other words, the formation and breaking of H-bonds in the energy band of our common environmental situation deliver the key for understanding life and its supporting element – water. It is also obvious that all major changes in water quality and temperature, for example, as a result of climate change, must have an influence on the dynamics of reactions and on the material balances involved. This again will influence the water cycle and hence the aquatic resources.

Here, water management comes into the focus. Different kinds of water use with different influences on water quality in small- or large scale must be considered. Industrial development and population growth have led to one of the biggest challenges to supply sufficient and hygienically safe water for human consumption and food production. Severe water shortage and necessary water quality are issues that have arisen regionally and are predicted to intensify drastically during the following decades. Concepts for multiple water use and water reuse need to be developed, taking advantage of the specific hydrological, climatic, and ecological situations. In addition, the special demands of social communities such as mega cities or developing countries have to be considered. Wherever possible, the ecological functions of regions must be protected for it is most reasonable to use nature as a self-sustained system also for water cleaning. The protective function of soils and their capability to degrade and eliminate aquatic pollutants make it attractive to use groundwater as a resource for drinking water supply, especially when protective zones and assisting technical measures are established.

Toxicity and hygiene reflecting criteria are, besides the technical aspects such as corrosivity, most important for the use of water. A meaningful assessment of the use-oriented water quality has also to include parameters which quantify, for example, biota friendliness, potential for bacterial growth, eutrophication, and disinfection by-product formation. Occurrence of pathogenic microorganisms and waterborne epidemic episodes belong to the most serious events often with peaks in wars, natural disasters, and badly managed camps, homes, and companies. Quite often, shortcuts between the systems for drinking water supply and wastewater discharge have been identified as reason.

Economic aspects are one of the master drivers for use of water and its management. On the one hand, the availability of enough water of suitable quality has been discussed as an issue of human rights. On the other hand, water has become a trade good, which is sold directly in bottles or through pipes or as virtual water in the manifold forms of industrial products. No matter how much profit might be involved in this business, the availability of reasonable resources and economically feasible treatment technologies will play a fundamental role. The application of cheap energy sources such as sun light and the use of homogeneous and heterogeneous catalysis, including biocatalysis, lead to most promising water-treatment concepts.

Intelligent combination and an optimized sequence of treatment steps can further improve the economy of water plants. Hybrid systems are suited for highly efficient water treatment in fast working small reactors with the advantage of decentralized application.

Keeping these aspects in mind, it becomes obvious that understanding the details of the properties of living and nonliving water constituents, their reactivities, and transport behavior will help to tailor powerful methods for water-quality assessment and to derive efficient concepts for timely water-treatment processes. The water cycle is an ideal case study not only for its different stages and hot spots, but also as a whole which can teach us the systematic approach to complex systems and to the solutions of the related man-made problems.

It also shows the necessity of transdisciplinary thinking in the sense of lifelong learning. Starting in the early days of childhood, we need to lay the foundation for a responsible care for water as a basis for our life and culture.

Furthermore, we need to invest in the tools for a sustainable water management by developing measures to save the water cycle in its proper ecological function. This calls for the classical components of teaching and research and beyond that for innovative concepts to serve the daily needs of water usage in an economically affordable and socially acceptable way.

To serve this aim, a comprehensive treatise on water is presented. Volume 3 of this work includes the chemistry and microbiology of MoWaS. The analytical aspects cover water-specific sum parameters, methods for the determination of trace metals and metalloids, as well as radioactive substances, and the characterization of natural organic matter (NOM). Emerging contaminants, colloids, and engineered nanoparticles are presented and data handling is described. The identification of bacteria and parasites helps to characterize the hygienic status of water. Online monitoring, screening of estrogen activities, and enzyme-linked immunotests show the way to modern concepts for continuous quality control and bioeffect-related assessment. The development and application of standardized methods supply tools to obtain reproducible and well-comparable results. For the special needs of water treatment and distribution, it is most useful to quantify biodegradability and toxic effects. Reaction mechanisms of oxidation and disinfection processes as well as bioremediation are important not only to understand the pathways of technical transformations and natural attenuation, but also to optimize treatment strategies. All these topics are addressed by leading experts in the field. They all intend to supply for the interdisciplinary water community the molecular facts for a meaningful diagnosis of the status of aquatic systems and for efficient technical processes within the water cycle.

As the editor of this volume, I would like to thank all the authors for their valuable contributions. Furthermore, I am grateful to U. Bilitewski, T. Bünger, G. Donnevert, G. Gauglitz, H. Geckeis, B. Hambsch, T. Hofmann, H. Horn, T. P. Knepper, D. Knopp, V. Neitzel, R. Nießner, B. Nowack, F. Petry, H.-J. Pluta, M. Spiteller, and M. Weller for their input by peer-review.

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Preface – Water-Quality Engineering

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Water technology has been ever growing. It is an essential set of technologies for sustainable human society. Traditional technology, or better called just skill, to obtain, purify, and supply water was developed in the ancient era in various regions of the world. Great efforts have been made to obtain safe and adequate water as an essential resource to human life. However, still, billions of people in the world have no access to safe water. Moreover, large numbers of people have no chance to use a proper sanitation system, and this eventually deteriorates water quality and decreases the available safe water resources.

Water resources are renewable theoretically. Used water does not disappear but is renewed to freshwater through evaporation by the power of solar energy. Solar energy is a natural distillation system to remove impurities present in water. However, the help of water technology is needed to maintain this renewing function in the modern world in which human activity overwhelms the natural purifying function.

Conventional water technology was used as a black box through which water was purified without knowing the mechanisms, which control the physical, chemical, and biological reactions used in purification. However, such empirical use of technology cannot further improve or develop the technology. Many researchers and practitioners have developed theory-based technology, rather than mere empirical skill, for purifying water. The function of each unit process was studied and the mechanisms of separation, role of microorganisms, and process characteristics were clarified. A significant amount of knowledge has been accumulated. This knowledge improves process performance and reliability. Human beings also developed tools to examine the micro- or nanoscale reaction. Modern technology needs to be based on a deep and broad understanding of theory.

Water technology is not isolated from other technologies. Many innovations to upgrade water-technology performance have been tried by applying new technologies from other fields. Membrane technology that originated in a field such as medical science or chemical engineering is an example. Nowadays, water treatment is one of the largest application areas of membrane technology.

The purpose of water technology has been expanded from purification of water to water generation, energy and resource recovery. This is a practical and important area to which new technology can be applied. Water availability is limiting human settlements. The supply of water produced from seawater or even moisture can break through this limitation.

The requirements for water technology differ very much from one place to the other. The key factors are target compounds to be removed, resource and energy consideration, capacity of operating human resources, as well as economic resources. For example, a safe water-supply system in least-developed areas needs technology, which can be used without frequent and sophisticated maintenance. However, such technology does not mean cheap and old technology. Newly developed innovative technology has a higher chance of implementation than old technology.

Water management needs policy and system technology rather than simple connection of unit technologies. A distributed wastewater treatment system needs reliable and economically and technologically reasonable treatment technologies. A nutrient removal policy for eutrophication can be realized by introducing a technologically reasonable combination of secondary and advanced treatments. The water technology is a system technology.

Resource and energy limitation has become a key factor for sustainability. Substantial amount of material use threatens the world's resources, and energy use provokes the climate change problem. Saving resource and energy is now an indispensable aspect of water technology. The necessity of energy and resource saving further changes water technology. The current global situation regarding climate change and resource limitation enhances the recovery of resource and energy. Wastewater contains organic matter, which is biomass; therefore, obtaining carbon-neutral energy is possible.

Water technology is now forming an important part of business worldwide. Every country needs safe water and environmental protection from wastewater. Technology development, implementation, and maintenance provide substantial opportunities for business.

This volume includes theory, practice, and recent development of these wide range of water technologies, although all such innovative technologies cannot be included. There is no single answer to any of the particular cases. Among many options, one should choose a technology system considering the local social, economic, and engineering aspects. This volume would help such a technology choice.