Scale of water resources development and sustainability: small is beautiful, large is great

Demetris Koutsoyiannis

Department of Water Resources and Environmental Engineering, Faculty of Civil Engineering, National Technical University of Athens, Greece
dk@itia.ntua.gr

Received 18 November 2010; accepted 14 March 2011; open for discussion until 1 December 2011

Citation Koutsoyiannis, D. (2011) Scale of water resources development and sustainability: small is beautiful, large is great. *Hydrol. Sci. J.* **56**(4), 553–575.

Abstract Several aspects of water resources and their links with food and energy supply, as well as with natural hazards, have been obscured due to political aims and ideological influences. At the same time, the involvement of politics and ideology testifies to the high importance of water-related issues internationally, and reflects the intensifying unresolved problems related to water, food and energy adequacy, as well as protection from floods and droughts. In an attempt to separate, as much as possible, the essence of problems from the political and ideological influences, several facts and fallacies about water and interrelated issues are discussed, based on data (numbers) rather than on dominant ideological views. The domain of the discussion is generally the entire globe, but, as a particular case, Greece, whose water resources are only partly developed, is discussed in more detail. From a pragmatic point of view, the water infrastructure in developed countries appears to be irreplaceable, although its management is adaptable toward more environmentally-friendly operation. For developing countries, no alternative to large-scale water resources development by engineering means appears plausible. The recent pursuit of renewable energy makes imperative the utilization of the existing and, where possible, the building of new, large hydropower plants, as only these can provide efficient energy storage, which is necessary for the renewable energy provided by nature in highly varying patterns.

Key words water resources; water needs; scale of development; dams; reservoirs; hydropower; renewable energy; energy storage

Echelle du développement des ressources en eau et durabilité: petit est beau, grand est bien

Résumé Plusieurs aspects concernant les ressources en eau et leurs liens avec les productions alimentaire et énergétique, ainsi qu'avec les risques naturels, ont été occultés à cause de stratégies politiques et d'influences idéologiques. Parallèlement, l'intégration de la politique et de l'idéologie confirme l'importance majeure des enjeux de l'eau au niveau international, et reflète les problèmes croissants et irrésolus de l'adéquation entre eau, alimentation et énergie d'une part, de protection contre les inondations et les sécheresses d'autre part. En tentant autant que possible de faire la part des choses entre le fond des problèmes et les influences politiques et idéologiques, nous discutons plusieurs faits et erreurs relatifs à l'eau et aux corollaires sur la base de données (chiffres) plutôt que selon les points de vue idéologiques dominants. La discussion a une portée globale, mais le cas particulier de la Gréce, dont les ressources en eau ne sont que partiellement développées, est discuté en détail. D'un point de vue pratique, les infrastructures hydrauliques apparaissent être irremplaçables dans les pays développés, même si leur gestion peut être adaptée et être plus respectueuse de l'environnement. Pour les pays en développement, aucune alternative au développement à grande échelle par l'ingénierie des ressources en eau n'est plausible. La priorité récente aux énergies renouvelables rend impérative l'utilisation, lorsqu'elles existent, et la construction, lorsque c'est possible, de centrales hydro'lectriques puissantes, dans la mesure où elles constituent le seul stockage efficace d'énergie, nécessaire pour une énergie renouvelable fournie par la nature.

Mots clefs ressources en eau; besoins en eau; échelle du développement; barrages; réservoirs; énergie hydroélectrique; énergie renouvelable; stockage de l'énergie

ISSN 0262-6667 print/ISSN 2150-3435 online

doi: 10.1080/02626667.2011.579076
http://www.informaworld.com

INTRODUCTION

Nothing can be green without water—except 'green' politics (Vít Klemeš 2007)

Impressive proof of the importance of water-related issues in the international political agenda is provided by a recent report by US and EU Intelligence Agencies (NIC & EUISS, 2010) about the so-called global governance. They state: "*At the beginning of the century, threats such as ethnic conflicts, infectious diseases, and terrorism as well as a new generation of global challenges including climate change, energy security, food and water scarcity, international migration flows, and new technologies—are increasingly taking center stage*". At least half of these threats and challenges are directly related to water. The report provides more detailed data about water and its interrelationship with other issues of global political importance, i.e.:

> The water situation is a major driver behind food scarcity. Water use is closely intertwined with food production. Today, 40 percent of the world's food supply comes from land that is irrigated, but most irrigation is highly inefficient in water use. As population and average per capita water use have grown, the amount of fresh water withdrawn globally each year has grown too—from 579 cubic kilometers in 1900 to 3973 cubic kilometers in 2000. Demand is projected to rise further to 5235 cubic kilometers by 2025. Over one billion people live in areas where human use of available water supplies has exceeded sustainable limits; by 2025 this figure will rise to 1.8 billion, with up to two-thirds of the world's population living in water-stressed conditions, mostly in non-OECD countries. Climate change will compound the scarcity problem in many regions as precipitation patterns change and many populous areas become drier.

Evidently, politics are closely related to ideologies. Environmentalism, the now-dominant ideological current and social movement, focusing on environmental conservation and improvement, and emphasizing a duty to save the planet from diverse threats, has also determined the social views of water-related problems and solutions. Most of them are regarded "politically correct", but sometimes this "correctness" may be a euphemism, if not a synonym for irrationality. A neat criticism of such views has been recently provided by the late Vít Klemeš (2007):

> [A] new infectious disease has sprung up—a WATER-BORN SCHIZOPHRENIA: on the one hand, we are daily inundated by the media with reports about water-caused disasters, from destructive droughts to even more destructive floods, and with complaints that 'not enough is done' to mitigate them and, on the other hand, attempts to do so by any engineering means—and so far no other similarly effective means are usually available—are invariably denounced as 'rape of nature' (often by people with only the foggiest ideas about their functioning), and are opposed, prevented, or at least delayed by never ending 'environmental assessments and reassessments'. In the present 'green' propaganda, all dams are evil by definition, ranking alongside Chernobyls, Exxon Valdezes, 'rape of the environment', AIDS, cancer and genocide.

History teaches that, within political agendas and their supporting ideologies, it is difficult to distinguish stated aims from means. For example, with reference to the report of NIC & EUISS (2010) mentioned above, it is difficult to interpret the statements: "*Another cluster of problems—the management of energy, food, and water resources—appears particularly unlikely to be effectively tackled without major governance innovations*" and "*no overall framework exists to manage the interrelated problems of food, water and energy*". Is the solution of water and interrelated problems an aim dictating global governance innovations as means, or are aims and means reversed? Whatever the answer to this question is, whenever political aims and ideological views are involved in scientific and technological issues, the latter become difficult to study as such. Klemeš (2008), examining the relationship of political pressures in scientific issues and in water resources management stated: "[P]*olitical pressures often set the agenda for what is to be (or not to be) predicted, and sometimes even try to impose the prediction result thus transforming prediction into prescription.*"

With such difficulties clarified, I will attempt in the next sections to approach, in a manner as rational as I can, some (eight) facts related to water resources and their development, as well as some (eight) fallacies, which I think have become widespread mainly because of ideological influences. Apparently, what I present is not free of personal opinions and I am not free of ideological influences. I endorse the importance of environmental conservation and improvement, as well as sustainability, which includes investing in renewable energy, sufficiency of, and equity in, food and water supply, and quality of life. I do not dispute the fact that small-scale constructions have smaller adverse environmental impacts (i.e. "small is beautiful") when viewed as isolated projects. However, viewing isolated items of a composite landscape is misleading, and, thus, the appropriate scale of development should be approached in a holistic manner, in view of the local and global conditions. Naturally, the dilemmas on water resources development and the questions about the appropriate scale of development concern mainly areas of the world not already developed. Certainly, the negative (and positive) experiences from the already developed areas should be taken into account in exploring the opportunities and directions in less-developed areas. However, just applying currently dominant ideological views, developed by people who live in the luxury of advanced (and, in effect, unquestioned) infrastructure, brings to mind a land owner who, after building his villa, prevents the neighbours from building in their own lands, which he regards as an extension of his garden.

To avoid biased opinions, as much as possible, the discussion of facts and fallacies that follows is based on data (numbers) rather than on dominant ideological views, although the latter may be mentioned when contradicted by the data. The domain of the discussion is generally the entire globe, but, as a particular case, Greece is discussed in more detail for three reasons: first, because it is a place where water resources have been partly developed and there is much potential for further development; second, because the stagnancy in water resources development in the last decades reflects a more general stagnancy of the country's economy, which has recently made it a frequent headline in international news; and third, because my knowledge of the local conditions is naturally better than that of any other part of the world.

FACTS

Fact 1: The world population is large and keeps growing

As shown in Fig. 1 (upper), the world population, from 1.6 billion in 1900, now approaches 7 billion and is expected to be 9 billion by 2050. As depicted in Fig. 2, the rate of population growth varies. A very high rate is seen for 10 countries, mostly African and South Asian (Burundi, Laos, Liberia, Afghanistan, Eritrea and others), while for 27 countries, mostly East European (Moldova, Montenegro, Ukraine, Slovenia, Georgia, Russia and others) the rate is negative. From Fig. 2 (lower), it can be seen that there is at least one quantifiable determinant of the population growth: the rate of population growth is negatively correlated to the income (gross domestic product—GDP). Evidently, other factors (cultural, birth control) influence the growth rate, but these are more difficult to quantify.

Fact 2: People prefer to live in large cities

From Fig. 1 (upper), we can observe that the rural population in the most developed areas of the world (Europe, Australia, North America and Japan) has been slightly but systematically declining, and that even in the entire world the rural population tends to stagnancy. Therefore, all of the future population growth is expected to be concentrated in the urban areas of the world.

Megacities and megalopolitan conurbations with 10 million or more residents are becoming more numerous, predominantly, but not exclusively, in developing countries. Currently, there are 26 megacities with populations of over 10 million, as shown in Fig. 3, along with some of the smaller cities. There are 63 cities with populations of over 5 million, 476 cities with populations of over 1 million and about 1000 cities with populations of over 500 000.

The trend of the population to move to large cities is more characteristically depicted in Fig. 1 (lower). As shown in Fig. 1 (lower), for any specified population, the number of cities that exceed it has increased by more than two orders of magnitude in the last two centuries (notice that in 1800 only one city had population over 1 million, London). The improved urban infrastructure, predominantly urban water infrastructure, has played a major role in the urbanization trend. The trend testifies to the fact that life in large cities has advantages (to which I can add my personal testimony, as I have lived most of my life in Athens, with a population of 4.5 million, but I have also lived for 12 years in a small village with less than a thousand people). This fact is reflected even in language where several positive qualities are etymologized from the Greek "πόλις" (*polis*) = city and the Latin *civis* = townsman, i.e. πολίτης (*polites*) = citizen; πολιτεία (*politeia*) = state, republic; πολιτική (*politike*) = policy, politics; πολιτισμός (*politismos*) = civilization.

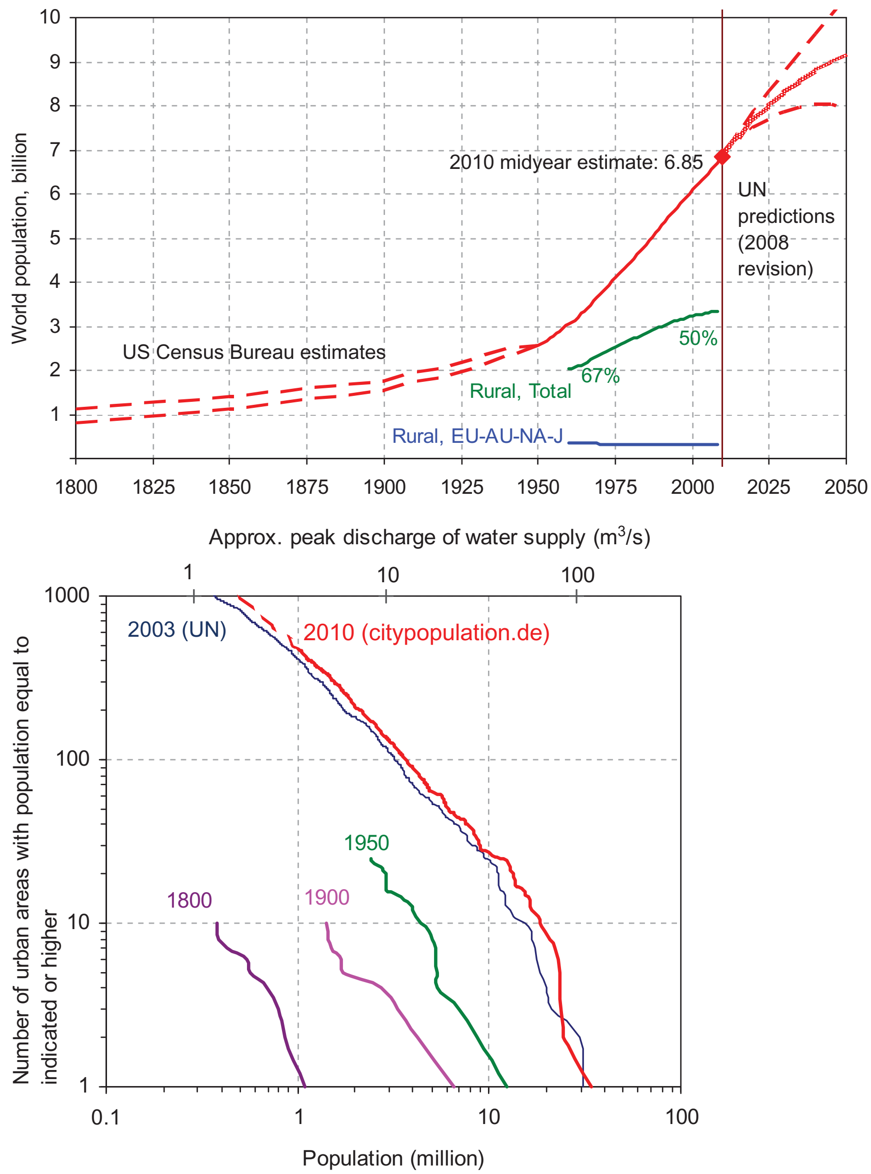

Fig. 1 (Upper) Historical evolution and future estimation of world population (EU, AU, NA and J stand for Europe, Australia, North America and Japan; data sources: esa.un.org/unpp/p2k0data.asp; www.census.gov/ipc/www/worldhis.html; www.census.gov/ipc/www/idb/worldpop.php). (Lower) Statistical distribution and historical evolution of the number of large cities (data sources: www.mongabay.com/cities_urban_01.htm; www.citypopulation.de/world/Agglomerations.html; geography.about.com/library/weekly/aa011201f.htm); the order of magnitude of cities' water supply peak discharge is also plotted (assuming peak consumption of 300 L/d per capita).

Fact 3: People need water to drink and support quality of life

While human water needs are a self-evident truth, it is also true that disparities in water supply among different parts of the globe are marked: in developed countries, any person may have a water supply through household connections, and consumes typically 150–200 L/d, and in some cases up to 1000 L/d. However, in developing countries, it constitutes only a target to provide "reasonable access" to water, which is meant to be 20 L/d per capita at a distance of less than 1 km. (Interestingly, comparison with standards in the Athens of the 7th century BC, which, as implied by Solon's legislation, are 2 × 20 L/d at a distance of less than 740 m—Koutsoyiannis *et al.*, 2008b—indicates a stagnancy, or even regression, over 27 centuries.) Unfortunately, 18% of the world population (>1 billion) do not have this "standard" (Howard & Bartram, 2003).

The real reasons of such disparities are astonishingly misunderstood by the wider public and

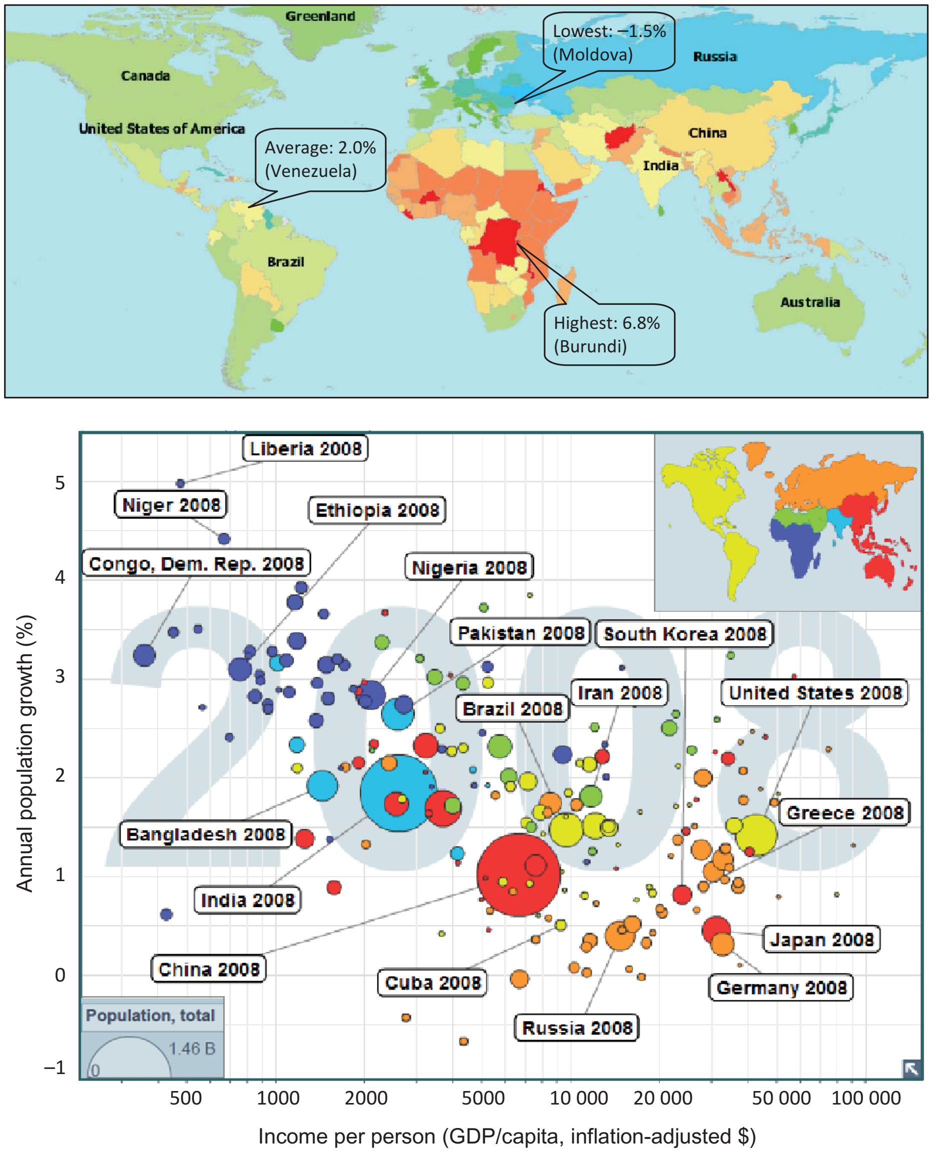

Fig. 2 (Upper) Estimated population growth for the period 2005–2010 (source: world.bymap.org/UrbanPopulationGrowthRates.html). (Lower) Percentage of annual population growth for each country *vs* country's GPD per capita; the size of each circle indicates the population of the country (see key at the left-bottom corner; data source: World Bank; data availability and visualization from Gapminder World, powered by Trendalyzer from www.gapminder.org).

decision makers, as is exemplified by the following Introduction to the so-called European Declaration for a New Water Culture (www.unizar.es/fnca/euwater/index2.php?idioma=en):

> We live in times of crisis in which the international community must pause to reflect and decide which model of global governance we must take on board for the 21st century. We must face up to the ever worsening crisis of social and environmental unsustainability in the world. With reference to water resources, the systematic destruction and degradation of water ecosystems and aquifers has already led to dramatic social repercussions. 1100 million people with no guaranteed access to drinking water, and the breakdown of the hydraulic cycle [*sic*] and health of rivers, lakes and wetlands are two consequences of this crisis.

The fact that there is no breakdown of the hydrological cycle (assuming that this is meant by "hydraulic cycle") is readily recognized by anyone who has a basic hydrological knowledge. Also, it may not need much depth of knowledge to understand that the destruction and degradation of water ecosystems is not the

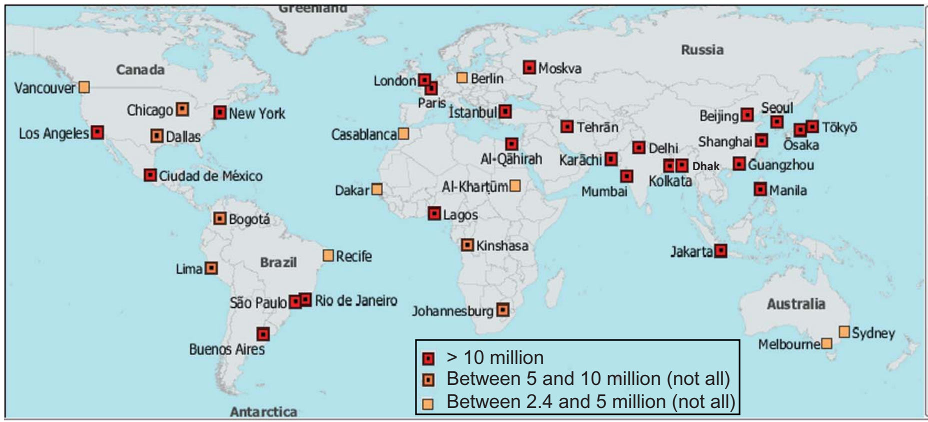

Fig. 3 The principal urban agglomerations of the world (adapted from Brinkhoff, T., *The Principal Agglomerations of the World*, www.citypopulation.de).

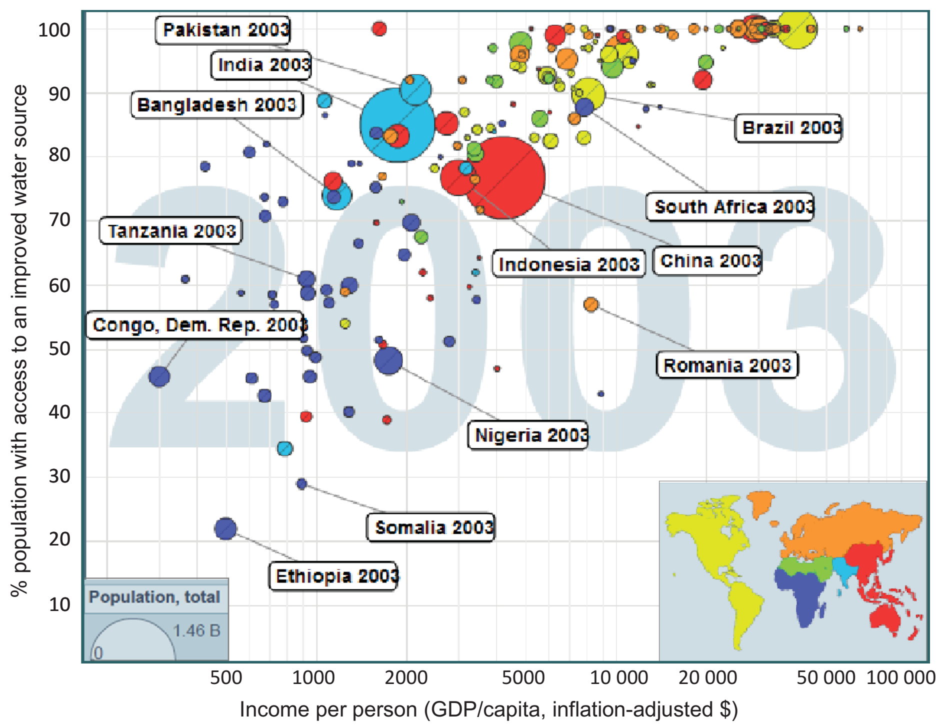

Fig. 4 Percentage of population with access to an improved water source for each country *vs* country's GPD per capita; the size of each circle indicates the population of the country (see key at the bottom-left corner). Improved water source includes household connection, public standpipe, borehole, protected well or spring, and rainwater collection (data source: World Development Indicators; data availability and visualization from Gapminder World, www.gapminder.org).

reason for the poor (or lack of) water supply of more than 1 billion people. Some data may help explain the real reasons. As shown in Fig. 4, the percentage of population with access to an improved water source is correlated to the GDP. People in developed countries have proper water supply, mostly by household connections. With very few exceptions, in countries with GDP of US$10 000 per capita, 100% of the population achieves this high living standard, regardless of the specific value of GDP. In poorer countries, this percentage depends on the income (GDP), and is very low in the poorest African countries.

This suggests that water scarcity is economy-driven, i.e. it is caused by lack of investment in water, or else lack of technological infrastructure for water. This is clearly seen in the classification of Fig. 5, where, except for (not densely populated) arid areas where water scarcity is physically driven, the water scarcity is due to economic reasons. The same story is depicted in Fig. 6, taken from a recent study by

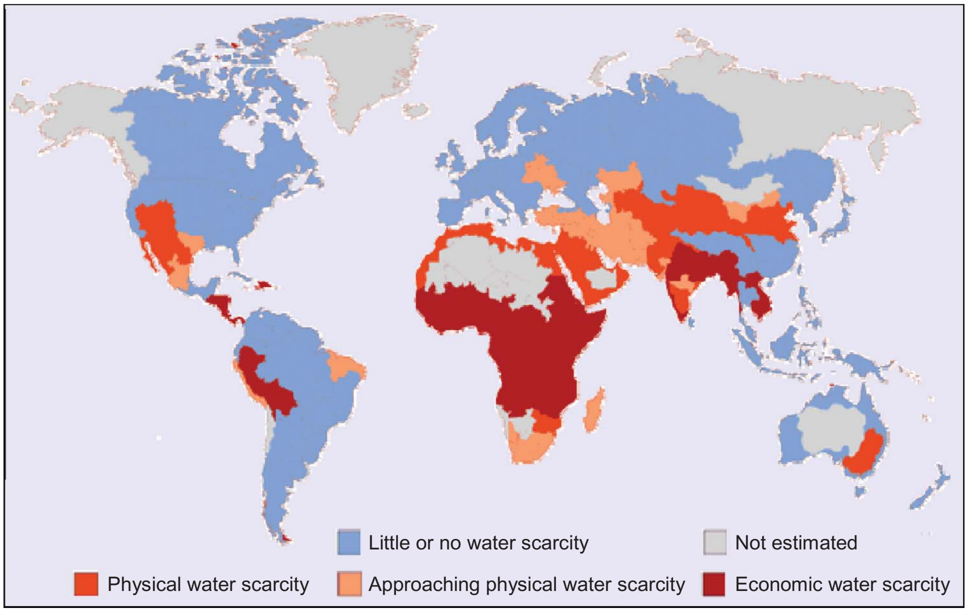

Fig. 5 World distribution of water scarcity (adapted from FAO Water Development and Management Unit – Graphs & Maps, www.fao.org/nr/water/infores_maps.html; www.fao.org/nr/water/art/2007/scarcity.html; original source: Comprehensive Assessment of Water Management in Agriculture, 2007).

Vörösmarty *et al.* (2010). Comparing Europe and Africa in this figure, it is observed that, considering natural factors (upper panel of Fig. 6), Europe is more water deficient (shows a higher threat index) than Africa, but when technological infrastructure for storing and distributing water is considered (lower panel of Fig. 6), the picture is fully reversed and agrees with that of Fig. 5. Interestingly, Vörösmarty *et al.* (2010) advocate, for developing countries, "*integrated water resource management that expressly balances the needs of humans and nature*". However, they do not seem to suggest technological means different from those already used in developed countries. Earlier, in the same tune, Takeuchi & Simonovic (1998) had assessed that the development of surface water reservoirs in developing countries (similar to those already built in developed countries) will be indispensable, regardless of environmental concerns.

Fact 4: People need water for health

It is widely recognized that modern sanitation (with proper sewer systems and wastewater treatment plants) has greatly contributed to the improvement of public health and increased life expectancy. However, again for economic reasons, the percentage of world population using improved sanitation is very low in the poorest countries (Fig. 7). As a result, half of the urban population in Africa, Asia and Latin America suffers from diseases associated with inadequate water and sanitation (Vörösmarty *et al.*, 2005).

Recognizing the poor economic situation and the lack of technological infrastructure as the real reasons for water scarcity and health problems, we can expect that economic progress, wherever and whenever it is made possible, will lead to improved water availability and sanitation in developing countries. Here, Athens can serve as an encouraging example. Due to its dry climate (annual precipitation 400 mm, no rivers with permanent flow), the water supply in Athens depends on a large-scale engineered system (four reservoirs) bringing water from distances >200 km (see Fig. 12, lower). Investments for the construction of this system have always been given the highest priority. Up to the 1970s, the city did not have a proper sewer system; even big apartment blocks were served by sewage tanks that were emptied by sewage trucks. A master plan, elaborated in 1979 by the English engineering firm J. D. & D. M. Watson, suggested that the entire replacement of sewage tanks with a sewer network system would be prohibitively expensive and that the tanks should remain in the less densely-populated areas. However, 10 years later, the sewage tanks were entirely replaced by a modern sewer network system. Today, the city has both a proper sewer network and wastewater treatment.

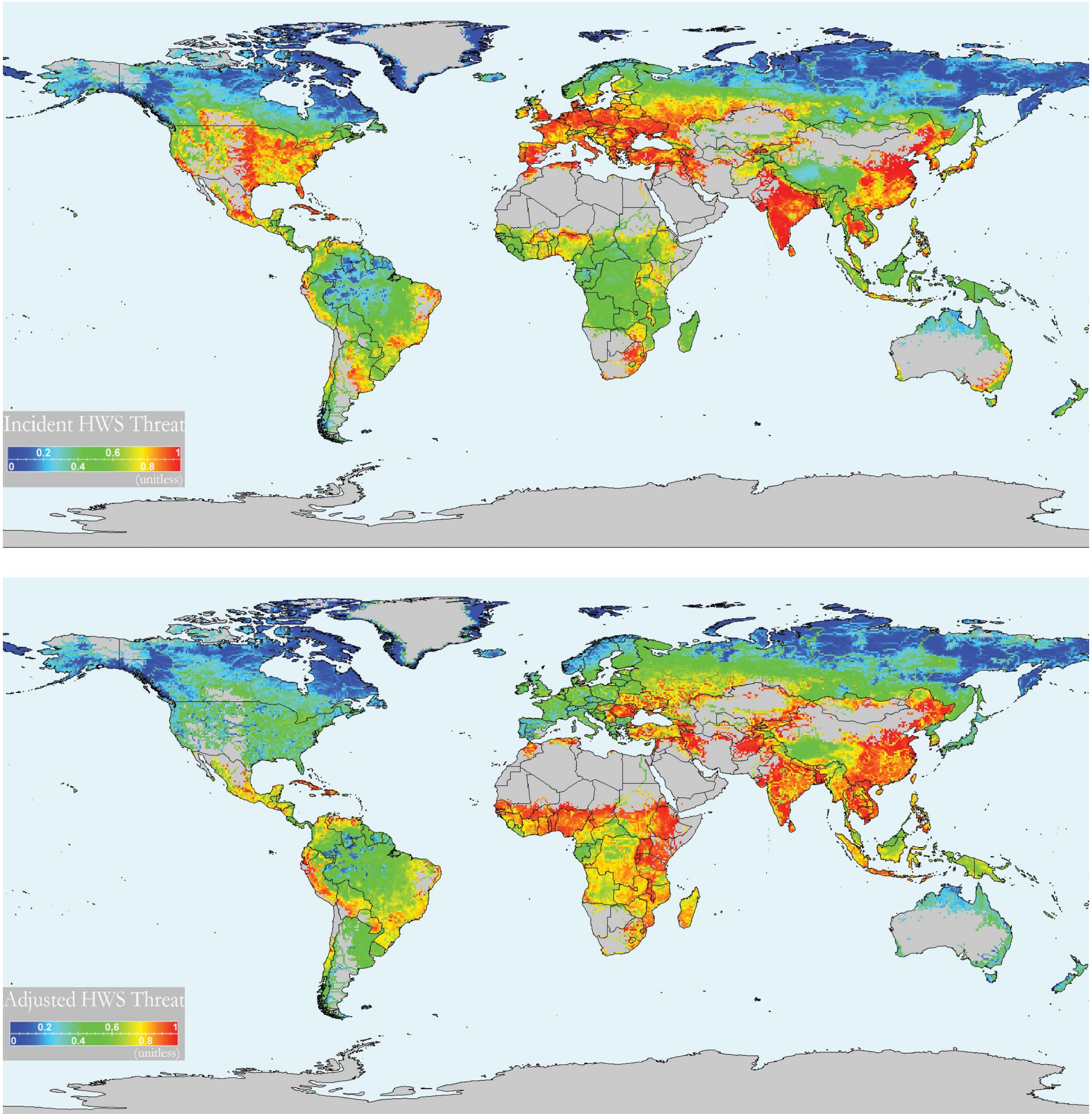

Fig. 6 World distribution of human water security (HWS) threat: (upper) as appears naturally and (lower) after accounting for water technology benefits (source: Vörösmarty *et al.*, 2010, as available for download in www.riverthreat.net/data.html).

Fact 5: People need water to eat (to produce food)

While municipal water supply has the highest quality requirements, in terms of quantity it constitutes a small percentage of total water withdrawals (Fig. 8). Most of the water consumed worldwide goes to irrigation. As illustrated in Fig. 8 (lower), the portion of agricultural water use depends on climate—not on income. In countries with high population and intensive irrigated agriculture, such as India, Pakistan and, to a lesser degree, China, water resources are insufficient to cover irrigation needs, and this problem is expected to worsen due to increased population in the future.

Water demand management is an option that helps mitigate water deficiency (Saleth, 2011; this

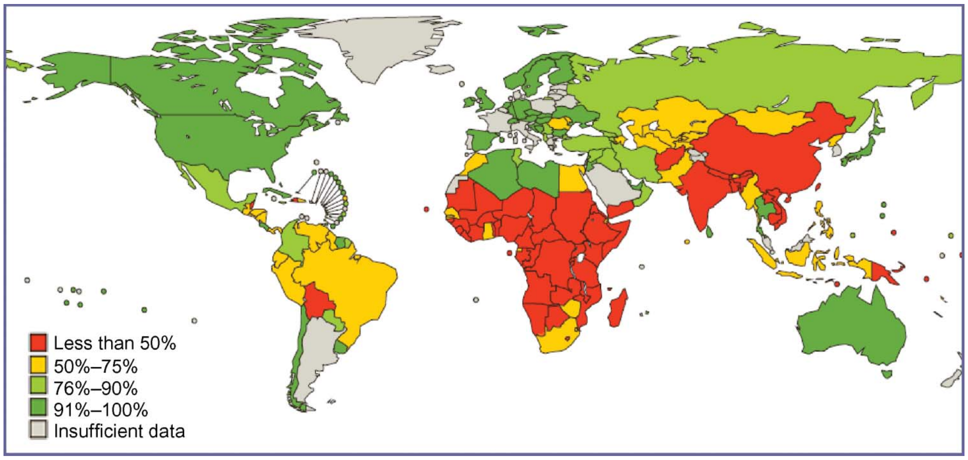

Fig. 7 World distribution of the percentage of population using improved sanitation (data from 2003; source: UNICEF & WHO, 2004).

issue), but it cannot tackle the problem alone, without further water resources development. Certainly, demand management is environmentally friendlier than the construction of new projects, but it is also costly. The most effective tools of demand management, such as water saving by replacing traditional irrigation methods with micro-irrigation, and by implementation of metered water pricing, need appropriate infrastructure.

Fact 6: People need to be protected from floods

When urbanization is not combined with urban water infrastructure, the results are tragic, not only in terms of economic damages due to floods, but also in terms of flood fatalities. This has been demonstrated recently by Di Baldassare *et al.* (2010) for Africa, where flood fatalities have increased by an order of magnitude in the last 60 years, an increase equal to that of the urban population. Urban engineering infrastructure should, thus, include flood protection works and urban planning.

Fact 7: People need to be protected from droughts and famines

Long-lasting droughts of large extent are intrinsic to climate (cf. Hurst-Kolmogorov dynamics; Koutsoyiannis *et al.*, 2009b). Such droughts may have dramatic consequences, even to human lives, as shown in Table 1, which refers to drought-related historical episodes of "food availability decline" (famines). Large-scale water infrastructure, which enables multi-year regulation of flows, is a weapon against droughts and famines. As shown in Table 1, famines and their consequences have been alleviated through the years owing to improved water infrastructure and international collaboration.

Fact 8: People need water for energy

Electricity has been a foundation of current civilization, and hydroelectricity, which represents about 16% of total electricity, has been a cornerstone for reasons that will be explained in the following sections. As shown in Fig. 9, both total electricity and hydroelectricity have been increasing exponentially with rates 3% (meaning doubling every 25 years) and 2.6% per year, respectively. In Europe and the USA, hydroelectricity has been stagnant, but in several countries in Asia and South America its increase has been spectacular (> 6% per year; Fig. 9).

The question arises, then, why Europe's hydroelectric production has been stagnant. Is it related to the dominant ideological views disfavouring the building of new dams and large hydro-projects, or even favouring the demolition of existing dams? Some data to study these questions are provided in Table 2. The most developed countries (Germany, France, Italy, Switzerland, Spain, Sweden) have already developed almost all their economically-feasible hydro-potential (80–100%) and, thus, there can hardly be further increase. Norway has exploited a smaller percentage (67%), which, however, already represents about 99% of its total electricity (data from www.bp.com/productlanding.do?categoryId=6929&contentId=7044622). In terms of the second question, indeed it may be necessary to demolish old dams, as any man-made construction, after some time for safety and economic reasons (although there is an ancient dam that, not having collapsed, still

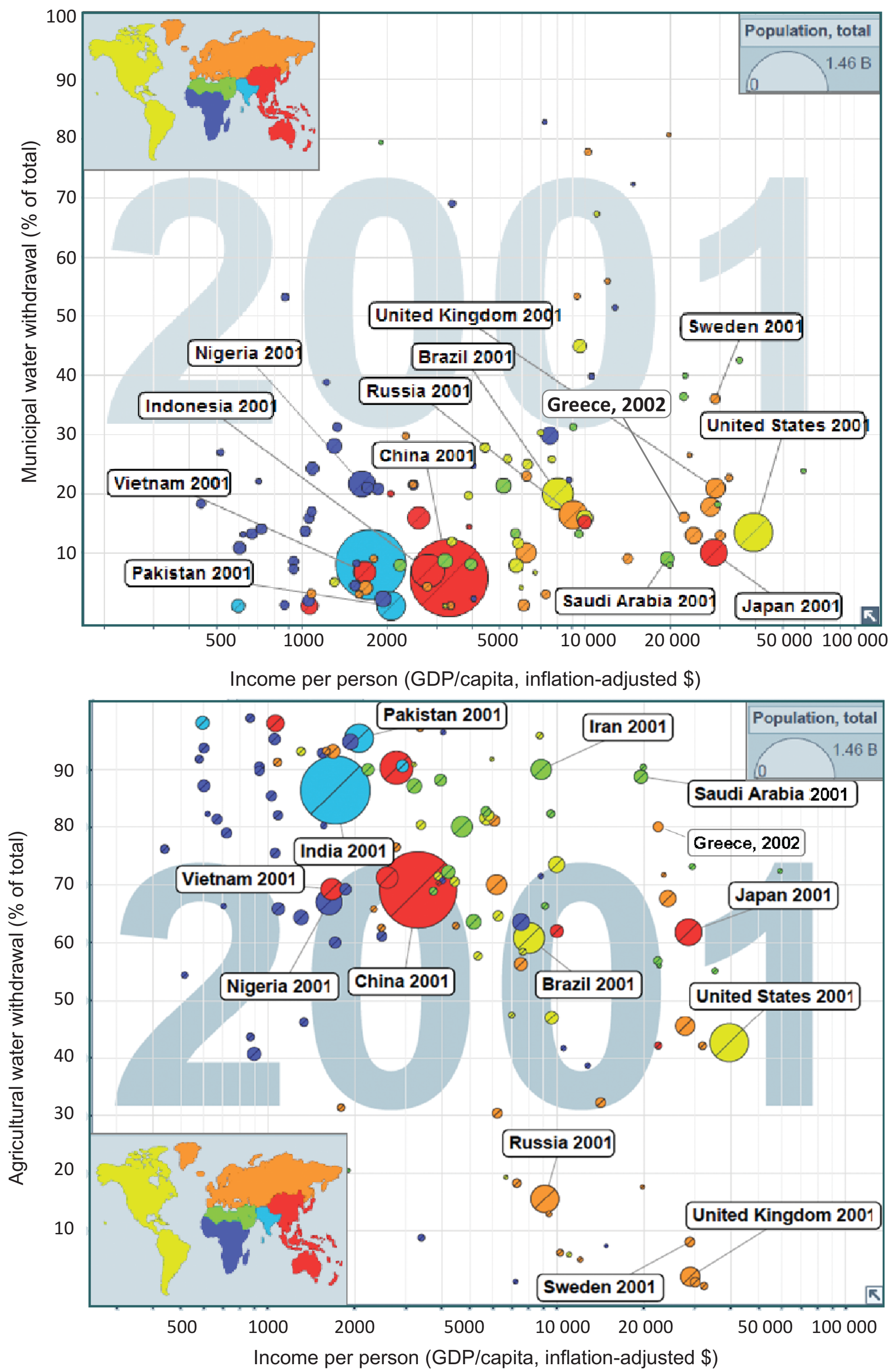

Fig. 8 Percentage of water withdrawals for municipal and agricultural use (upper and lower panels, respectively) for each country *vs* country's GPD per capita; the size of each circle indicates the population of the country (see key at the top-right corner; data source: FAO aquastat database; data availability and visualization from Gapminder World, www.gapminder.org).

stands after about 2.5 thousand years; Koutsoyiannis *et al.*, 2008b). In addition, there are intensifying discussions that dam removal has significant environmental benefits for the restoration of aquatic ecosystems and native fisheries. An Internet search will gather information from multiple sources that hundreds of dams have already been dismantled in an attempt to restore the health and vitality

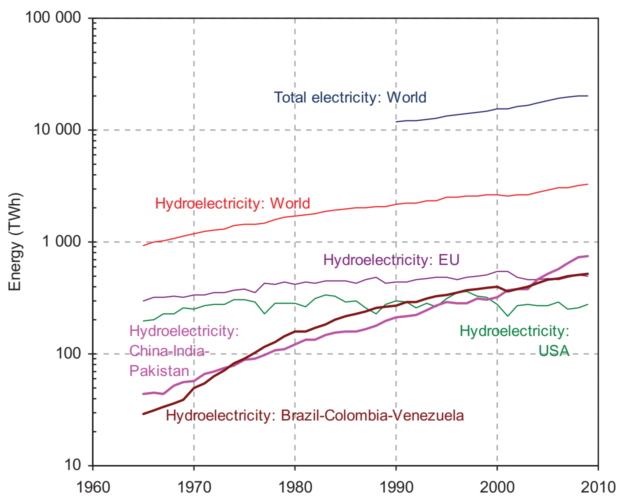

Fig. 9 Evolution of total electricity and hydroelectricity in the world and in particular groups of countries in the last 45 years (data source: www.bp.com/productlanding.do?categoryId=6929&contentId=7044622).

of rivers. However, a more careful examination of specific data or photos of "dams removed" (e.g. commons.bcit.ca/recovery/global.html; www.americanrivers.org/2008DamRemovals) will reveal that these are small and rather old constructions that could be rather called barrages or embankments (with heights from less than a metre to a few metres). To my knowledge, no large hydro-project has ever been demolished for environmental restoration. However, magnifying stories of embankment demolition may provide a fictitious element of realism of the environmentalist ideology, which may be necessary for its conservation.

The last row of Table 2, that refers to Greece, deserves more detailed discussion. Greece's low exploitation percentage of hydropower potential (31%) would allow for spectacular development of hydroelectricity, as, for example, in South American countries. In addition, the multi-purpose character of hydropower projects would also help resolve water scarcity problems. This raises the question: Why has Greece's hydroelectric production been stagnant? The answer to this question should be sought in the mimetism—at the ideological rather than the pragmatic level—of Greek society and politics for European stereotypes, that did not enable water resources development in recent decades. This mimetism is very strong in the Greek "green" groups, which fanatically oppose water infrastructure projects. (Recently, private energy companies may have been added to the opponents of hydropower projects, whose operation pushes energy prices down during water-rich periods; www.energypress.gr/portal/resource/contentObject/id/bd4974a8-00b8-47ea-9472-eb64388ae09f.) The most impressive example, with the dimensions of a Greek tragedy, is the Mesochora project (170 MW, 340 GWh/year, investment 500 M€; shown in Fig. 12) in the Upper Acheloos River (Koutsoyiannis, 1996; Stefanakos, 2008). The dam and the hydropower plant have been constructed and have been, in effect, ready for use since 2001. However, they have not been put into operation, thus causing a loss of 25 M€/year to the national economy (assuming the lowest price of renewable energy, i.e. 73 €/MWh imposed by decree in Greece—see below).

Table 1 Most devastating famines in the last 150 years (sources: Devereux, 2000; de Marsily, 2008; Center for Research on the Epidemiology of Disasters, www.emdat.be).

Period	Area	Fatalities (million)	Fatalities (% of world population)
1876–1879	India	10	
	China	20	
	Brazil	1	
	Africa	?	
	Total	>31	>2.2%
1896–1902	India	20	
	China	10	
	Brazil	?	
	Total	>30	>1.9%
1921–1922	Soviet Union	9	0.5%
1929	China	2	0.1%
1942	India	1.5	0.06%
1943	Bangladesh	1.9	0.07%
1965	India	1.5	0.04%
1973	Ethiopia	0.1	0.003%
1981	Mozambique	0.1	0.002%
1983	Ethiopia	0.3	0.006%
1983	Sudan	0.15	0.003%

Table 2 Data of economically feasible and exploited hydropotential in European countries (data from Leckscheidt & Tjaroko, 2003, in general, and Stefanakos, 2008, for Greece).

Country	Economically feasible hydro-potential (TWh/year)	Production from hydro-plants (TWh/year)	Exploitation percentage (%)
Germany	25	25	100
France	72	70	97
Italy	55	52	95
Switzerland	36	34	94
Spain	40	35	88
Sweden	85	68	80
Norway	180	120	67
Greece	15	4.7	31

Table 3 Data of economically feasible and exploited hydropotential in the world (data from Leckscheidt & Tjaroko, 2003).

Continent	Economically feasible hydro-potential (% of world)	Exploitation percentage (%)
Europe	10	75
North & Central America	13	75
South America	20	30
Asia	45	25
Africa	12	8

There is unexploited hydro-potential, similar to Greece's or greater, in many countries in South America, Asia and Africa, as shown in Table 3. Therefore, the principal dilemma, as to whether or not this potential should be exploited by large-scale projects, has to be resolved—although countries recently becoming increasingly powerful, such as China, India, Pakistan, Brazil, Colombia and Venezuela, seem to have already resolved it, as shown in Fig. 9.

FALLACIES

Fallacy 1: Groundwater constitutes the vast majority of freshwater

Reports from the media, and information provided to the wider public and decision makers, may not have been able to distinguish the feature of water to be a renewable resource from that of other natural resources (e.g. fossil fuels) which are subject to depletion. This misrepresentation has typically originated from graphs like that in Fig. 10, which shows where water is stored on Earth. Groundwater appears then as the vast majority of liquid freshwater, and surface water appears to be a negligible fraction—particularly water in rivers. Similar information appears in tabulated form (see e.g. the table at the bottom of the USGS information sheet at the URL shown in the caption of Fig. 10—notice the difference in the Greek translation in ga.water.usgs.gov/edu/watercyclegreek.html). The correctness of the information given in such graphs and tables is not questioned. However, in the case of renewable resources, as is freshwater, fluxes matter much more than storage. Surface water flux to the oceans is estimated at 44 700 km^3/year, whereas an estimate of groundwater flux to the oceans is 2200 km^3/year (Shiklomanov & Sokolov, 1985), that is, about 20 times less.

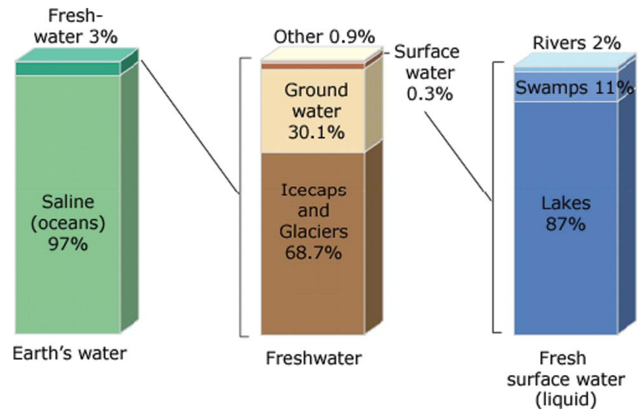

Fig. 10 A depiction of water distribution on Earth (from an information sheet of US Geological Survey—USGS; ga.water.usgs.gov/edu/watercyclehi.html) typical of the consideration of freshwater as a non-renewable reserve.

While the ratio 1:20 does not necessarily constitute an exact characterization of the relative quantities of groundwater and surface water in land, where moving water may switch from surface to ground and *vice versa*, it becomes clear that surface water, and particularly that of rivers, constitutes the vast majority of water that can potentially meet the human needs described above. However, there are huge technological differences in the exploitation of groundwater and surface water. In groundwater, the storage is provided by nature (aquifers) and the withdrawal can be done by a large number of small-scale technical works (wells) without the need of pipelines, unless the aquifer is far from the location of water use. In contrast, with the exception of endorheic basins that form lakes, storing streamflow requires a large-scale artificial system (dam – reservoir) and the withdrawal and distribution also requires large-scale pipe works. As a result, surface water projects need substantial financial investment. Also, they may have substantial impacts on the environment. However, this does not mean that groundwater exploitation is environmentally safer. In contrast, experience shows that some of the most adverse—and in effect irreversible—environmental impacts have been created by groundwater overexploitation, where sustainability is not spontaneous. For example, Vörösmarty *et al.* (2005) note: "*For most parts of the planet,* [the non-sustainable water use] *will refer to the 'mining' of groundwaters, especially in arid and semiarid areas, where recharge rates to the underground aquifer are limited*" (see Fig. 11 for a world map of unsustainable uses). As a characteristic example, Tiwari *et al.* (2009), using Gravity Recovery and Climate

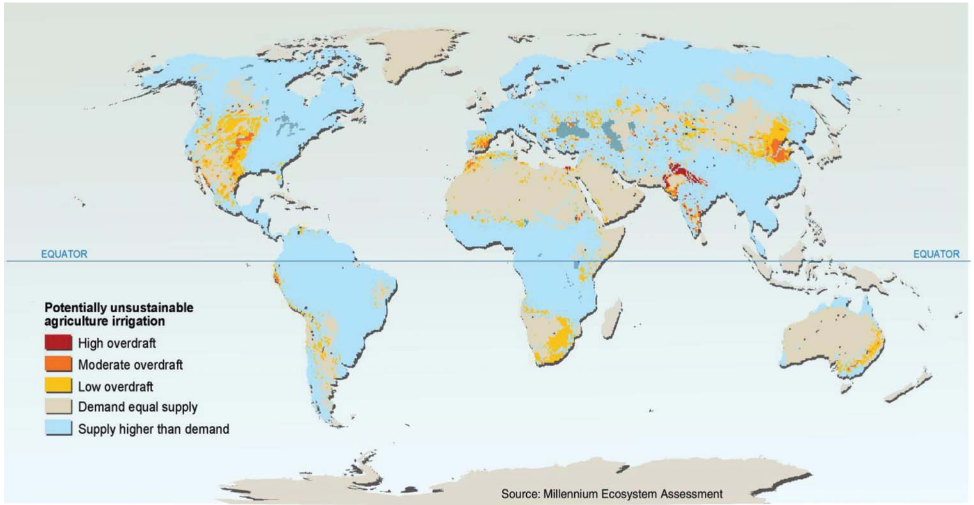

Fig. 11 World distribution of potentially unsustainable agricultural water use (source: Vörösmarty *et al*., 2005; Fig. 7.3, available on line and downloaded from www.maweb.org/en/GraphicResources.aspx). High and low overdrafts roughly correspond to >0.4 and <0.04 m/year, respectively.

Experiment (GRACE) satellite data, concluded that in northern India there is large-scale overexploitation of groundwater at a loss rate of 54 ± 9 km^3/year, probably the largest loss rate in any comparable-sized region on Earth. Groundwater overexploitation has sometimes been initiated by overestimation of basic hydrological quantities, such as aquifer recharge (see e.g. Fadlelmawla *et al.*, 2008, who report a case of a small aquifer in Kuwait which was initially exploited at a rate one order of magnitude higher than the sustainable yield). Even if a correct estimation is later obtained, it is difficult to stop groundwater overexploitation due to the so-called "tragedy of the commons" (Llamas, 2004) associated with selfish individualism. The apparent temporary winners in such situations are the wealthier who dig the deepest boreholes (Panda & Kumar, 2011). In the long term, though, there may be no winner.

Fallacy 2: Water transfer is non-sustainable

Problems related to overexploitation can hardly appear in surface water withdrawal: even in the most extreme (but not advisable) case, when a river or a reservoir dries, water withdrawal will necessarily stop (until water appears again). However, scholars and water managers, perhaps for the sake of symmetry, have devised a case of non-sustainable surface water use, which is the "interbasin transport". Thus, Vörösmarty *et al.* (2005, p. 169) state: "[non-sustainable water use] *can also embody the interbasin transport of fresh water from water rich to water poor areas*", although elsewhere in the same text (p. 184) they state: "*Interbasin water transfers represent yet another form of securing water supplies that can greatly alleviate water scarcity*". From a scientific point of view, the notion of "interbasin transport" seems not well defined and, rather, constitutes a stereotype. Several questions can therefore be raised:

(a) What does this stereotype represent? Do not scale, size and quantity matter? Is it "interbasin transport" when water quantity of 1 L/s is transferred between two neighbouring catchments of different streams, each having an area of, say, 1 km^2, at a length of, say, 1 km? Is it not "interbasin transport" when 10 m^3/s are transferred between two neighbouring sub-catchments of the same river, each having an area of, say, 10^4 km^2, at a length of, say, 100 km?
(b) What is the essential difference, in scientific terms, of "interbasin transport" from "intrabasin transport"?
(c) Can water be used by humans (as opposed to fish) without having been transported?
(d) Is it non-sustainable to alleviate water scarcity?
(e) Is it non-sustainable to substitute transferred surface water for water from overexploited groundwater sources?

In Europe, a usual argument against the implementation of interbasin water transfer plans is that the Water Framework Directive (WFD; European Parliament and Council of the European Union, 2000), by demanding river basin management plans, essentially adopts the river basin as the management unit. However, this argument is very weak. In fact, WFD designates as the main unit for management of a river basin the so-called "river basin district", which may be composed of more than one neighbouring river basins (Article 2(14)), whose definition depends on non-objective criteria. We may also observe that even the definition of the "river basin" in the WFD ("*the area of land from which all surface run-off flows through a sequence of streams, rivers and, possibly, lakes into the sea at a single river mouth, estuary or delta*"; Article 2(13)) is hydrologically insufficient, as it does not include endorheic river basins that have no outlet to the sea. However, the principal counter-argument is that, whatever the management unit is, it should not necessarily be considered as a closed system. It is difficult to imagine that, in an era of open skies, free trade, and globalization, we might convert river basins into entrenchments, disallowing water transfer into or out of the basins.

Fallacy 3: Virtual water trade is more sustainable than real water transfer

Virtual water is the water "embodied" in a product, i.e. the water needed for the production of the product; it is also known as "embedded water" or "exogenous water", the latter referring to the fact that import of virtual water into a country means using water that is exogenous to the importing country (to be added to a country's "indigenous water"; Hoekstra, 2003). Worldwide, international virtual water trade in crops has been estimated at 500–900 km^3/year, while current rates of water consumption for irrigation total 1200 km^3/year (Vörösmarty *et al.*, 2005). It is generally regarded that "*virtual water trade is a realistic, sustainable and more environmentally friendly alternative to real water transfer schemes*" (Hoekstra, 2003). There is no doubt that virtual water trade can be a realistic and sustainable option. However, the statement comparing it, in general terms, with real water transfer may not have the proper depth of analysis and penetration of a scientific statement. Some questions may aid understanding of this:

(a) Assuming that virtual water transfer is realistic and sustainable, why is real water transfer not?
(b) Can the two transfer options, virtual water and real water, be compared in general and stereotypical terms (i.e. without referring to specifics, such as quantity, distance, energy, etc.)?
(c) Is it really more sustainable and more environmentally friendly to transport agricultural products at distances of thousands of kilometres, consuming fossil fuel energy, than to transfer real water (albeit, evidently, a much larger quantity thereof) at distances of a few kilometres, producing energy?
(d) Is international trade more sustainable than boosting local agricultural production and improving local economies?
(e) Is sustainability achievable, irrespective of resilience in crisis situations (economic crises, international conflicts, embargos, etc.)?

The current global economic crisis—and Greece's crisis in particular—may emphasize the importance of the last question. Again using Greece as an example, older people still relate stories about massive numbers of deaths from famine in Athens during the two world wars, whereas people living close to agricultural areas did not face food adequacy problems.

A more contemporary interesting case, illustrating the situation in Greece, is offered by the history of the Acheloos interbasin transfer plan. Acheloos is the largest river in Greece in terms of discharge (4370 hm^3/year; Koutsoyiannis *et al.*, 2001). The river has been segmented and its flows regulated since the 1960s by the construction of the large dams, shown in Fig. 12 (upper). A plan for further development includes the transfer (by a 17.4-km-long tunnel toward the east starting from the Sykia Dam, marked by an arrow in Fig. 12, upper) of about 15% (600 hm^3/year) of the Acheloos flows to Thessaly, the biggest and most water-deficient plain of Greece. The plan also includes four hydropower plants; two can be reversible, boosting production by up to 1000 GWh/year (converted to equivalent primary energy; Koutsoyiannis, 1996). The project has been under construction for more than two decades (since 1988), but it cannot be completed. Greek and European "greens" have fanatically fought the project. A web search for *Acheloos crime* would reveal that the project is regarded as a crime against the environment. Even a virtual "trial of Acheloos" was organized in 1996 by Greenpeace, WWF and three other "green" NGOs. Actual trials in the Supreme Court thwarted the government's plans several times, and the government had to repeatedly change the project design

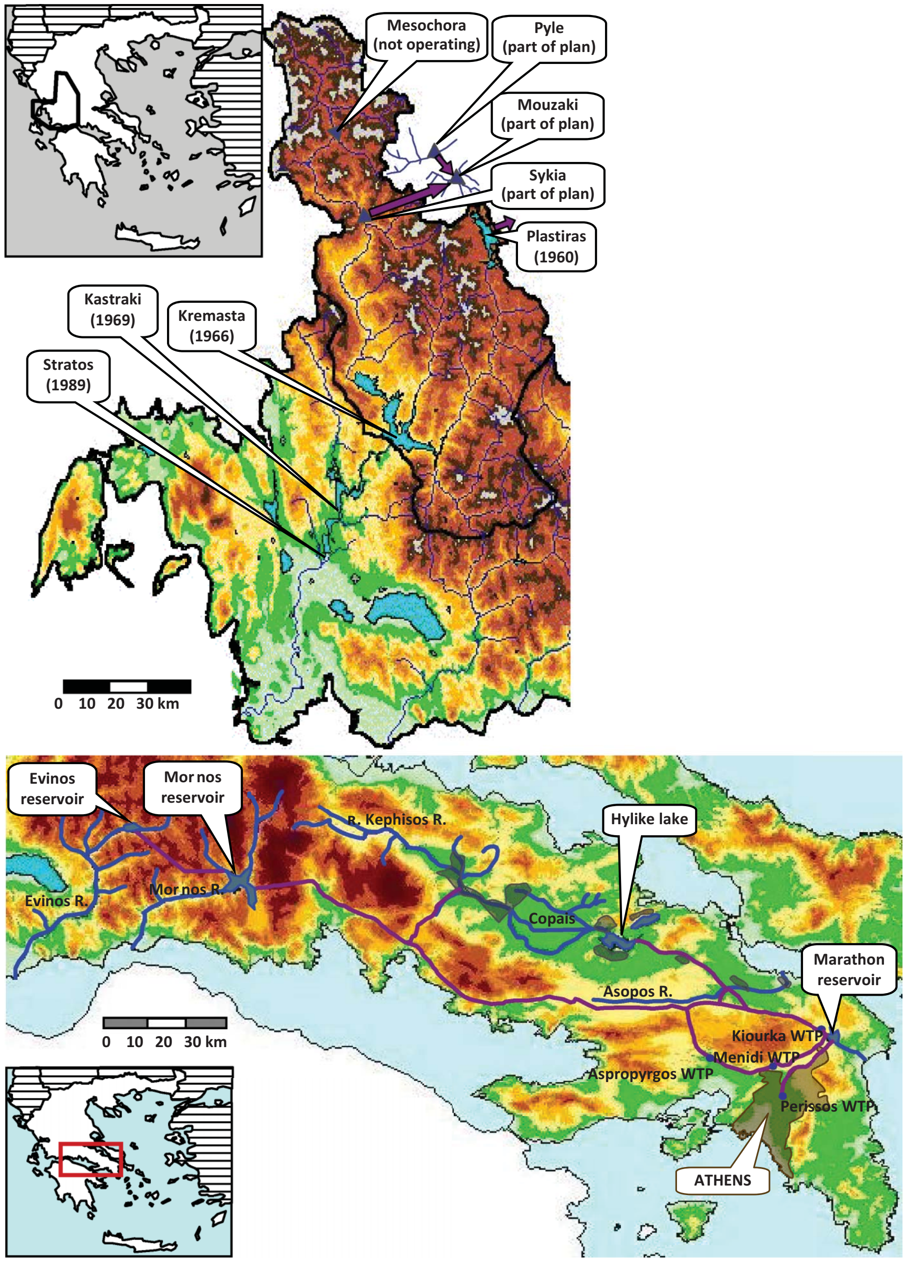

Fig. 12 The two largest hydrosystems of Greece: (Upper) The Acheloos system with existing and planned projects annotated; violet arrows indicate the planned water transfer. (Lower) The Athens water supply system with the four reservoirs and the four water treatment plants (WTP) annotated; grey shaded areas indicate aquifers whose water is also transferred to Athens; violet lines represent the water transfer paths.

studies to comply with the court directives. It may be didactic for Greeks to compare this story with that of a much bigger plan in India, the National River Linking Project (see Saleth, 2011; this issue). When completed, this will be the largest water infrastructure project ever undertaken in the world. It will connect 37 Himalayan and Peninsular rivers through 30 links, involving 3000 storage dams and 12 500 km of water conveyance networks, and handling 178 km^3 of inter-basin water transfers. Lacking governmental initiative to start implementing the project, the Supreme Court of India, acting on public interest litigation, directed the central government in 2002 to constitute a task force and complete the project by 2012. That is, the pressures from the public and the Supreme Court in India are in exactly the opposite direction from those in Greece—and, evidently, the results in terms of economic development are also in opposite directions.

Interestingly, in Greece, no opposition was encountered for the transfers for the water supply of Athens, shown in Fig. 12 (lower). The total quantity of transferred water approaches 500 hm^3/year (not counting virtual water, whose quantity is tremendous), about the same order of magnitude as in the Acheloos case. However, the overall scale of interbasin transfer is much larger in Athens: it involves four river basins and distances of more than 200 km (an order of magnitude higher than in Acheloos). In addition, while the Acheloos plan contributes with substantial energy production, in the Athens case we have substantial energy consumption due to pumping. An explanation for the lack of opposition to this project, part of which was completed in the 2000s, should not be sought in more prudent handling by the government or in more effective public consciousness, participation and consultation. Perhaps the Athens-based pressure groups see no "environmental crime" when their own water supply is put into question.

In addition, no opposition has ever been raised for virtual water trade. The current conditions of virtual water trade in Greece are illustrated in Table 4. The total transfer of virtual irrigation water (exports + imports) is 6750 hm^3/year, roughly equal to the total real irrigation water used in Greece (6860 hm^3/year; Koutsoyiannis *et al.*, 2008a). The Acheloos planned interbasin transfer of real water is one order of magnitude less (600 hm^3/year) and, if materialized, would contribute to a better balance of Greece's virtual water trade. The currently strongly negative balance of virtual water (–1971 hm^3/year, as shown in Table 4) reflects the fact that Greece, traditionally an agricultural country, has become counterproductive. Some of the entries in Table 4 are shocking, for instance the strongly negative balance (about –500 hm^3/year) of Greece with France—a country with substantial industrial production, part of which is also imported to Greece.

Table 4 Virtual water trade balance of Greece (hm^3/year; Source: Roson & Sartori, 2010).

Trading country	Exports	Imports	Balance
Albania	83.4	4.7	+78.7
Croatia	16.7	3.0	+13.7
Cyprus	52.0	5.3	+46.7
Egypt	5.4	91.4	−86.0
France	45.0	541.9	−496.9
Italy	242.3	171.3	+71.0
Morocco	0.9	4.9	−4.0
Spain	36.1	121.6	−85.5
Tunisia	1.1	4.2	−3.1
Turkey	30.9	143.1	−112.2
Rest Europe	1662.3	890.5	+771.8
Rest MENA	49.5	42.7	+6.8
Rest World	165.3	2337.5	−2172.2
Total	2390.9	4362.0	−1971.1

Fallacy 4: Seawater may become a future freshwater resource by desalination

In an attempt to provide alternatives to substitute large-scale surface water projects, "green" groups sometimes promote desalination as a future freshwater resource. However, as seen in Fig. 13, currently, only rich countries, mostly oil producing, have large-scale desalination plants. Desalination is costly and requires vast amounts of energy. In the future, depletion of oil will make desalination even more costly. Therefore, it is not a sustainable technology. Sometimes, an argument is offered that, if renewable (e.g. solar) energy is used, then desalination becomes sustainable. This, however, can be disputed on the basis that there is no excess of available energy and that, if additional renewable energy is to be produced, then it should be directed to cover existing needs, rather than creating additional energy consumption by desalination plants. Admittedly, though, desalination is a useful pragmatic alternative for some small-scale applications, e.g. small islands. In such cases, desalting brackish groundwater, which requires far less energy than seawater, or re-using non-traditional sources of water (e.g. treated wastewater) are other useful options, especially in water-stressed conditions (Koussis *et al.*, 2010).

Fallacy 5: Hydroelectric energy is not renewable and not sustainable

Since the water that produces hydroelectric energy is replenished, thanks to the perpetual hydrological cycle, and is not subject to depletion in the future, hydroelectric energy is clearly renewable and sustainable. However, business lobbying and "green" ideological influences have resulted in laws or regulations that define "small hydro" as renewable and sustainable, whereas "large hydro" is labelled as not renewable or not sustainable (Frey & Linke, 2002). Similar assertions have also been made in law scholarly articles, e.g. " . . . *large hydroelectric dams have been excluded because of their expense, their unreliability . . . , and the environmental damage that results from flooding large areas of productive and often populated lands and from the carbon dioxide released from decaying vegetation in the dam reservoir*" (Ottinger & Williams, 2002). This

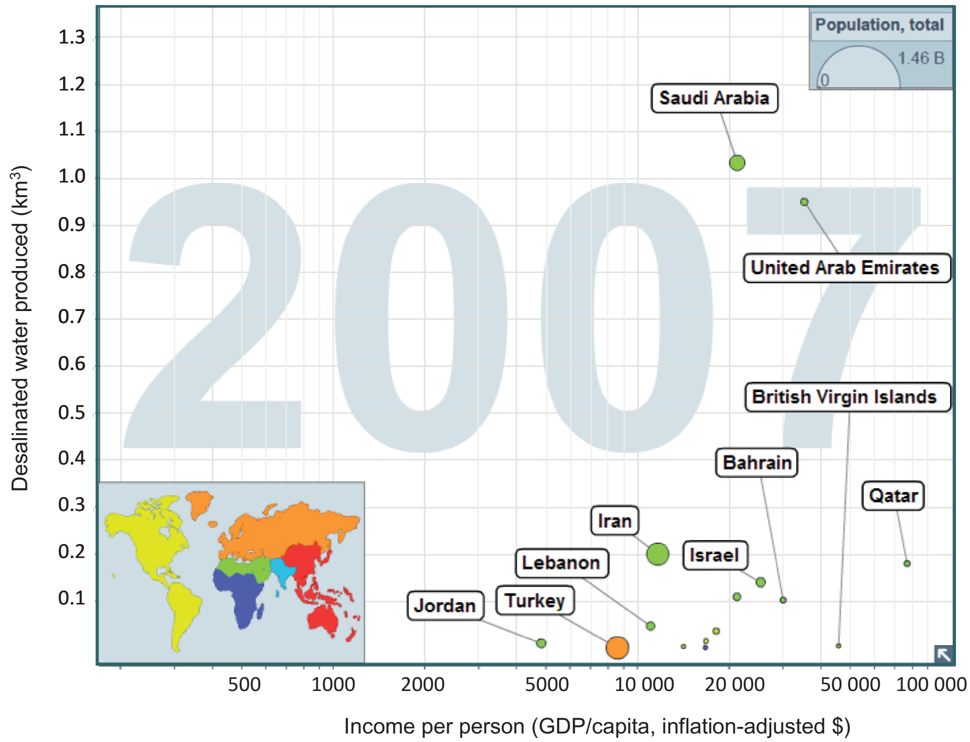

Fig. 13 Desalination water production for each country *vs* country's GPD per capita; the size of each circle indicates the population of the country (see key at the top-right corner; data source: FAO aquastat database; data availability and visualization from Gapminder World, www.gapminder.org).

fallacy is further exaggerated in "grey" literature, e.g. in internet sources of "green" origin: "*Hydro electricity is NOT renewable. Hydro dams irreversibly destroy wild river environments—while the water is renewable, wild rivers are not. Dams have a finite lifetime, but the wild river cannot be replaced*" (saveourwildrivers.org.nz/fact/hydro-electricity-not-renewable); "*Hydro power is not renewable. Hydroelectric power depends on dams, and dams have a limited life—not because the concrete crumbles, but because the reservoir fills with silt.*" (letters.salon.com/tech/htww/2009/07/07/wild_salmon_cause_global_warming/view/).

Evidently, economic interests, business lobbying and "green" ideology have been much more powerful than adherence to scientific reason in influencing political decisions and legislation. For example, according to the Greek legislation, "*The hydraulic power generated by hydroelectric plants, which have a total installed capacity more than 15 MW, is excluded from the provisions of this Act*" (Act 3468/2006 on the Production of Electricity from Renewable Energy Sources, Art. 27, par. 4, www.rae.gr/downloads/sub2/129(27-6-06)_3468.pdf; originally this limit defining what is renewable energy was 20 MW and a later law changed it to 15 MW). This law also determines prices for different renewable energies ranging between 73 and 500 €/MWh, which indicate a generous subsidy, given that even the retail price for household connections is lower (currently 53 €/MWh at night). Similar are the legislations in other European Union countries, only a few of which do not exclude large hydropower from their subsidy programmes (Reiche & Bechberger, 2004). The limit defining the small ("renewable") and large ("non-renewable") hydropower plants varies among countries (e.g. 10 MW in the UK, 5 MW in Germany, while The Netherlands has taken small hydro-plants off the list of renewables; Reiche & Bechberger, 2004). In the USA, the situation is similar, but the limit varies further (30 MW in California and Maine; 80 MW in Vermont; 100 MW Rhode Island and New Jersey; Égré *et al.*, 1999; Égré & Milewski, 2002).

Some simple questions may help show that the arguments advocating the non-renewable character of large-scale hydroelectric energy are pointless:

(a) What is the agent that makes the produced energy non-renewable when the installed capacity exceeds the limit imposed by legislation?

(b) Does reliability increase or decrease with the scale of the power plant?
(c) Were the dam and reservoir not constructed, would the carbon dioxide from naturally decomposing vegetation not be released to the atmosphere? (Are the trees not part of the natural carbon cycle and, thus, once grown, naturally subject to decay?)
(d) Even assuming that dams have destroyed river environments, does this make the energy they produce non-renewable?
(e) Does any human construction (including wind turbines and solar panels) have unlimited life?
(f) Will energy production stop if a reservoir is silted? (Will the hydraulic head disappear?)
(g) Is it non-sustainable to leave to future generations major assets and infrastructure for renewable energy production?

A more difficult question is: Why does legislation (in Europe and USA) exclude large-scale hydropower stations? This question becomes even more complicated because in some situations, e.g. in reporting the progress in achieving renewable energy targets, the contribution of large hydropower plants is not excluded. But to study this question would require a more thorough political analysis, which is beyond the focus of this paper.

Conversely, the argument about the damage to populated land is correct. Indeed, the population in inundated areas needs to be displaced. However, population displacement is not a case met in dams alone. Several major civil infrastructures may have similar impacts. In addition, displacement may happen also due to natural causes, such as landslides and unfavourable hydroclimatic shifts, as well as due to unfavourable economic conditions. Perhaps, the issue of population displacement has been given excessive emphasis because our modern societies tend to give priority to individual rights over collective rights, thus departing from the tradition which gave the word "idiot" (from the Greek "idiotes", meaning individual) such a negative meaning. Certainly, a better balance of collective and individual rights needs to be sought.

Large-scale constructions also cause large environmental changes (e.g. Hjorth *et al*., 1998). Thus, environmental concerns about dams and reservoirs are not pointless. However, the problems may not be irreversible and unresolvable. For example, recently, Vörösmarty *et al.* (2010) imply that negative impacts of dams can be reversed: "*Engineers . . . can re-work dam operating rules to maintain economic benefits while simultaneously conveying adaptive environmental flows for biodiversity.*"

In this respect, the environmental concerns and criticisms have helped explore and find solutions for real problems. These include:

(a) improved ecological functioning (permanent flow for habitats downstream of dams, improved conditions for habitats in reservoirs, passages of migratory fish);
(b) re-naturalization of outflow regime (see Fig. 14);
(c) sediment management by appropriate design and operation (sediment routing, by-pass or pass-through, sediment dredging and transport downstream; e.g. Alam, 2004); and
(d) revision (increase) of non-emptied reservoir storage for improved quality of water, ecosystems and landscape.

The latter point has been studied by Christofides *et al.* (2005) using as a case study the Plastiras Reservoir in Greece (Fig. 12, upper), which has an interesting story of changes. The project was designed for hydropower, but later, as it also provided water for irrigation and as the economy of the area became dependent on the water of the reservoir, the social and political pressure gradually shifted the reservoir's main objective; by 1990, it was the irrigation needs that dictated water management, reducing power production to a side-effect, and halving the economic value of the energy produced. Meanwhile, the scenery, combined with the geographical accessibility of the lake, attracted visitors and gradually tourist resorts were developed near the reservoir. The level and quality of water in the reservoir greatly affect the attractiveness of the area, and this resulted in pressures to keep the water level high, or increase the non-emptied storage and reduce withdrawals. This gave the environmental conservation high importance. Ecotourism attained high priority in the reservoir management and the place has become very popular even among "green" supporters, who sometimes overlook that it is not a natural lake but an artificial reservoir created by a large dam, and that one of the functions of this reservoir is the inter-basin transfer, quite similar to the more contemporary Acheloos plan (or "crime") discussed earlier. The story highlights the multi-purpose character, the wide range of options, and the flexibility of the management and adaptability to societal and environmental needs, of large-scale projects, which can hardly be met in small-scale ones.

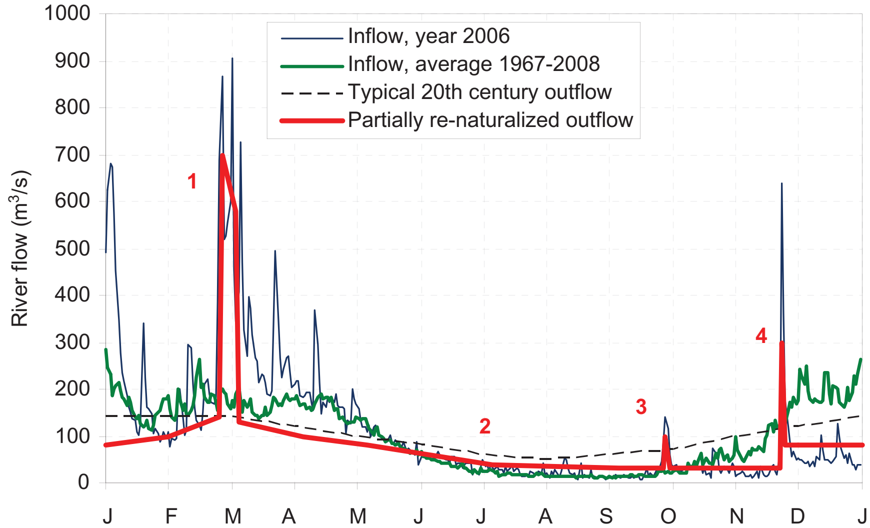

Fig. 14 Schematic of re-naturalization of dammed river flows based on ideas from Vörösmarty *et al.* (2005) and Tharme & King (1998). The river flow data refer to the Acheloos River at Kremasta dam (Fig. 12, upper). The natural inflows for a year (2006) and over the entire reservoir operation period (1967–2008) are shown, at daily scale, along with a typical 20th century outflow regime, which retains important hydrological characteristics, i.e. (1) peak wet season flood, (2) baseflow during the dry season, (3) flushing flow at the start of the wet season to cue life cycles, and (4) variable flows during the early wet season.

Fallacy 6: Large-scale energy storage is beyond current technology

While the notion of renewable energy is highly promoted, reference to its substantially different characteristics from non-renewable energies is often missed. Wind and solar energies (as well as that from small hydropower plants) depend on the weather, are highly variable and unpredictable, and cannot be synchronized with the variation of energy demand. Therefore, energy storage technologies, which can cope with this problem, are strongly needed, if solar and wind energy production is to increase.

It has been very common to read statements such as: "*Engineers haven't yet developed energy storage devices suitable for storing solar and wind power*" (Kerr 2010). However, pumping water to an upstream location consuming available energy, which will be retrieved later as hydropower, is a proven and very old technology with very high efficiency (Koutsoyiannis *et al.* 2009a; see also Table 5). This feature of hydropower makes it unique among all renewable energies. This technology can be implemented even in small autonomous hybrid systems (e.g. Bakos 2002). However, (for reasons explained below) it is substantially more advantageous in large-scale projects. A few of the existing cascades of hydropower plants have been designed and constructed as pumped storage plans, because the need for energy storage is not new. However, because,

Table 5 Energy efficiencies achieved by typical renewable and non-renewable technologies.

Energy	Remarks	Efficiency
Hydro	Large-scale (see text)	90–95%
Wind turbines	Betz limit (theoretical upper limit)	59%
	Achieved in practice	10–30%
Solar cells	Best research cells (three junction concentrators)	41.6%
	Commercially available (multicrystalline Si)	~14–19%
Non-renewable (for comparison)	Combined cycle plants (gas turbine plus steam turbine)	~60%
	Combustion engines	10–50%

typically, hydropower plants are used to generate only peak energy, and thus operate a few hours a day, there is potential to convert existing one-way plants into reversible ones, to be used for energy storage; however, this may need substantial investment, while it is much easier to design the new plants as reversible from the outset.

Fallacy 7: Hydroelectricity has worse characteristics than wind and solar energies

This fallacy may have been a side-effect of the exclusion of hydro-projects from renewable energy policies, as people tend to assume that there is some rationality even when irrationality dominates. However, it is easy to understand that the truth is just the reverse. Large-scale hydroelectric energy production has unique desirable characteristics among all renewables. It is the only fully controllable energy, as contrasted to the highly-variable and uncontrollable wind and solar energies. The element that enables control and regulation is the water storage in a sufficiently large reservoir.

Thus, this feature of hydropower is met only in large-scale projects and not in small hydropower plants. As a consequence of this feature, as well as due to the unique properties of hydromachinery (it can be turned on and provide full capacity within minutes), among all renewable and most non-renewable energies, only the hydropower plants offer high-value primary energy for peak demand. Also, as discussed above, they offer the unique option of energy storage. In addition, as shown in Table 5, hydroelectricity constitutes the only energy conversion (either renewable or not) with really high efficiency, approaching 95% for large-scale projects; other technologies have difficulty achieving even half of this value.

Fallacy 8: Small projects are better than large

The debate about large *vs* small projects seems to have been won by the latter; this is evident from daily news, from scientific documents and, in particular, from legislation. For example, in the last decade in Greece, while there was no noteworthy progress in the development of large-scale hydropower, a total of 250 small hydropower plants have been licensed, with a total installed capacity of 430 MW (Douridas, 2006). For comparison, the installed capacity of the old Kremasta hydropower plant in Acheloos (Fig. 12, upper) is larger, 437 MW. A question arises, what is less damaging to the environment? One large power plant, on one river (Acheloos), with an installed capacity of 437 MW, or 250 small power plants on different rivers and creeks, with a total installed capacity of 430 MW (1.7 MW each on the average)?

To study questions of this type in a more general setting, we can start from elementary knowledge of geometry, which reveals that if a certain volume V is divided into n geometrically similar shapes, the total area and the total perimeter will both be increasing functions of n; specifically, they will be proportional to n^s with $s = 1/3$ and $2/3$ for the total area and the total perimeter, respectively. This simple truth has implications on several fields, from the area occupied by reservoirs to the hydraulic losses in conduits, turbines and pumps.

Thus, we can expect that the occupied reservoir area per unit volume, or per unit installed capacity of the power plant, will be a power function of n, i.e. n^s with $s > 0$, where n is the number of individual elements to which a total volume or a total installed capacity is divided. As shown in Fig. 15, statistical analysis on existing hydropower projects with data from the literature, shows that the average reservoir area per unit installed power is larger in small projects, and fully supports the simple theoretical argument (with $s = 1/3$).

Likewise, the hydraulic losses in pipes, per unit area of pipe cross-section, will increase for decreasing size of pipe (because of the increase in wetted perimeter), and this will also hold for hydromachinery, i.e. pumps and turbines. Thus, the efficiency in energy conversion will be an increasing function of scale, and this is verified in Fig. 16 (upper), constructed from pump and reversible turbine data from the literature and an inventory of commercial pumps. These data can be described by expressions of the form $\eta = \eta_\infty - (\kappa\, Q)^{-\lambda}$, where η and η_∞ are the efficiencies for discharge, Q, and infinite, respectively, and κ and λ are parameters. In an average curve, $\eta_\infty = 0.93$, $\kappa = 3000$ m^{-3}s and $\lambda = 0.4$, whereas in an (upper) envelope curve, $\eta_\infty = 0.94$, $\kappa = 2800$ m^{-3}s and $\lambda = 0.6$.

Based on these equations, the total efficiency of a reversible (pumped storage) hydropower plant, expressed as a function of design discharge, Q, is shown in Fig. 16 (lower) after making some plausible assumptions on the hydraulic characteristics of

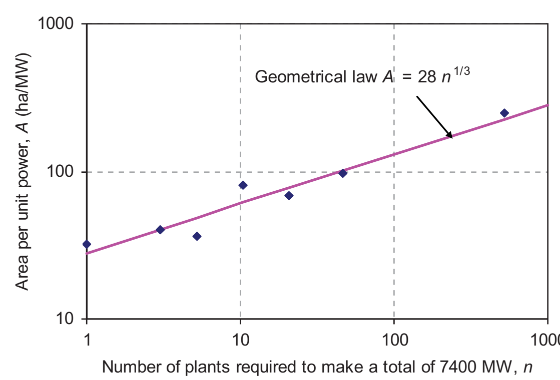

Fig. 15 Graphical depiction of reservoir area per unit power *vs* number of plants required to make a total of 7400 MW. The data are from an inventory of 188 existing hydropower plants, classified into seven categories by installed power (from Goodland, 1995, quoted in Égré & Milewski, 2002). Each point represents the geometrical mean of each category, where 7400 MW is the geometrical mean of the first category (plants with largest installed power).

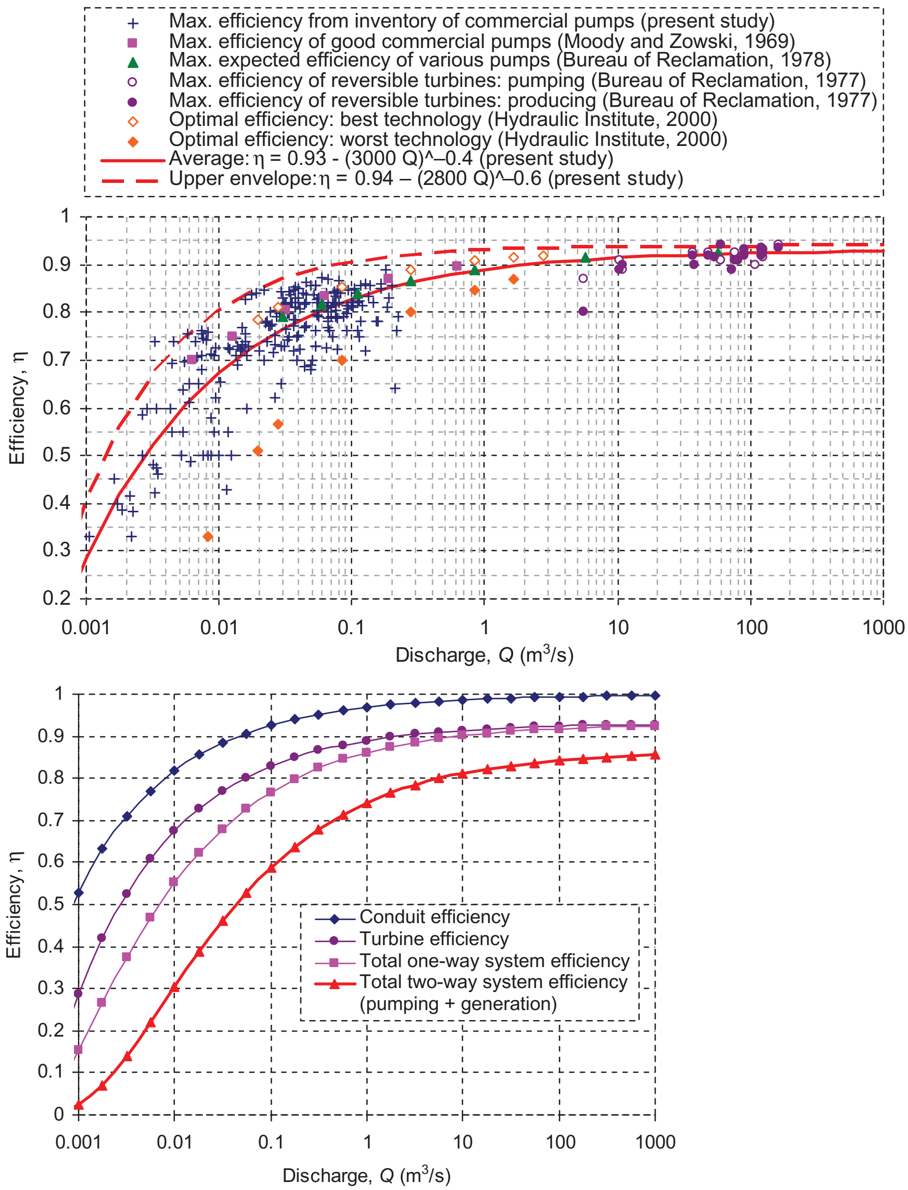

Fig. 16 (Upper) Efficiency of pumps and reversible turbines as a function of design discharge (data sources as indicated in the legend) and fitted mean and envelope curves. (Lower) An example of the partial and total efficiency of a hypothetical pumped storage plant *vs* the design discharge, Q; the calculations have been made according to the following assumptions: (a) turbine and pump efficiency according to the average curve, $\eta = 0.93 - (3000\ \mathrm{m^{-3}s}\ Q)^{-0.4}$, of the upper panel; (b) conduit length of 2 km and roughness of 1 mm; hydraulic head of 100 m; conduit velocity V varying as a power function $V(Q)$ of the discharge Q with $V(0.001\ \mathrm{m^3/s}) = 0.6\ \mathrm{m/s}$ and $V(1000\ \mathrm{m^3/s}) = 2.5\ \mathrm{m/s}$.

an example power plant, shown in the figure caption. Clearly, this figure shows the spectacularly increased efficiency in large-scale *vs* small-scale (discharge) and demonstrates that only large-scale systems can efficiently store energy.

CONCLUDING HIGHLIGHTS

- More dams are needed worldwide to meet increased water and food supply needs.
- More hydropower plants are needed to meet energy needs using the most effective and most efficient renewable technology.
- More reversible (pumped storage) plants are needed to meet energy storage needs and to make possible the replacement of fossil-fuel-based energy with renewable (and, hence, highly varying and uncertain) energy.
- More water transfer projects are needed to supply water to large cities and to partially replace virtual

water by real water and trade by local agricultural production.

- Large-scale water projects are superior, because only these are energy-efficient and multi-purpose, and because, in an holistic perspective, they can be less damaging to the environment than small-scale projects.

Acknowledgements I am grateful to the reviewer A. Koussis, the Guest Editor B. Sivakumar and the Co-editor Z. W. Kundzewicz, who also acted as a reviewer, for their constructive critiques and comments that led to improved presentation. I thank P. Hubert for providing general information, J. Stefanakos for providing data for Greece and discussing several important issues, D. Papantonis for providing information on pumps and K. Tzouka for her help in preparing an inventory of commercial pumps. I also thank A. Christofides, K. Hadjibiros, N. Mamassis, H. Theodosis, C. Vournas, Th. Xanthopoulos and V. Zoukos for their encouraging or critical comments and general discussions, mostly related to a presentation with the same title (or its preparation) at the *LATSIS Symposium 2010: Ecohydrology*, Lausanne, 2010; itia.ntua.gr/en/docinfo/1011/). Finally, I am grateful to the organizers of that symposium, M. Parlange, A. Rinaldo and M.-J. Pellaud, as well as A. Porporato, for the invitation to prepare and present a preliminary version of this work in the symposium.

REFERENCES

Alam, S. (2004) Sedimentation management in hydro reservoirs (keynote speech). Water India 4, Delhi (www.hydrocoop.org/publications/Sedimentation_Management_in_Hydro_Reservoirs.pdf).

Bakos, G. C. (2002) Feasibility study of a hybrid wind–hydro power-system for low-cost electricity production. *Appl. Energy* **72**, 599–608.

Bureau of Reclamation (1977) *Estimating Reversible Pump Turbine Characteristics*. Engineering Monograph no. 39, US Department of the Interior.

Bureau of Reclamation (1978) *Selecting Large Pumping Units*. Engineering Monograph no. 40, US Department of the Interior.

Christofides, A., Efstratiadis, A., Koutsoyiannis, D., Sargentis, G.-F. & Hadjibiros, K. (2005) Resolving conflicting objectives in the management of the Plastiras Lake: can we quantify beauty? *Hydrol. Earth System Sci.* 9 (5), 507–515.

Comprehensive Assessment of Water Management in Agriculture (2007) *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. London: Earthscan, and Colombo: International Water Management Institute.

de Marsily, G. (2008) *Ressources en eau dans le Monde : défis et persecptives*. Ougadougou: 2IE.

Devereux, S. (2000) *Famine in the twentieth century*. Brighton: Institute of Development Studies, IDS Working paper 105.

Di Baldassarre, G., Montanari, A., Lins, H. F., Koutsoyiannis, D., Brandimarte, L. & Blöschl, G. (2010) Flood fatalities in Africa: from diagnosis to mitigation. *Geophys. Res. Lett.*, doi:10.1029/2010GL045444.

Douridas, C. (2006) Development of an information system for small hydropower plants in Greece, Postgraduate Thesis, 85 pp., National Technical University of Athens, Athens.

Égré, D., Gagnon, L. & Milewski, J. (1999) Large Hydropower Projects: Renewable and Green? Hydro Quebec, (www.hydroquebec.com/sustainable-development/documentation/pdf/autres/pop_11_01.pdf).

Égré, D. and Milewski, J. (2002) The diversity of hydropower projects, *Energy Policy*, **30**, 1225–1230.

European Parliament and Council of the European Union (2000) Directive 2000/60/EC establishing a framework for Community action in the field of water policy. Official Journal of the European Communities, L 327, 72 pp.

Fadlelmawla, A., Hadi, K., Zouari, K. and Kulkarni, K. M. (2008) Hydrogeochemical investigations of recharge and subsequent salinization processes at Al-Raudhatain depression in Kuwait, *Hydrol. Sci. J.* **53** (1), 204–223.

Frey, G. W. & Linke, D. M. (2002) Hydropower as a renewable and sustainable energy resource meeting global energy challenges in a reasonable way. *Energy Policy* **30**, 1261–1265.

Goodland, R. (1995) *How to distinguish better hydros from worse: the environmental sustainability challenge for the hydro industry*. The World Bank.

Hjorth, P., Kundzewicz, Z. W. Kuchment L. S. & Rosbjerg D. (1998) Critiques of present reservoirs, Sec. 1.3.4 in *Sustainable Reservoir Development and Management*, Takeuchi, K., Hamlin, M., Kundzewicz, Z. W., Rosbjerg, D. & Simonovic, S. P., eds. Wallingford: IAHS Press, IAHS Publ. 251.

Hoekstra, A. Y. (2003) Virtual water: An introduction, in Virtual water trade. *Proceedings of the International Expert Meeting on Virtual Water Trade*, A. Y. Hoekstra, ed. Delft: IHE.

Howard, G. & Bartram, J. (2003) *Domestic Water Quantity, Service, Level and Health*. World Health Organization.

Hydraulic Institute (2000), HI Centrifugal Pump Design and Application—Figure 1.75A, (www.pumps.org/uploadedFiles/Pumps/About_Pumps/Pump_Diagrams/f01-75ab.pdf).

Kerr, R. A. (2010) Do we have the energy for the next transition. *Science*, **329** (5993), 780–781.

Klemeš, V. (2007) 20 years later: what has changed—and what hasn't. *XXIV General Assembly of the International Union of Geodesy and Geophysics*, Perugia, International Union of Geodesy and Geophysics, Wallingford: International Association of Hydrological Sciences.

Klemeš, V. (2008) Political pressures in water resources management: do they influence predictions? *International Interdisciplinary Conference on Predictions for Hydrology, Ecology, and Water Resources Management*, Prague.

Koussis, A. D., Georgopoulou, E., Kotronarou, A., Lalas, D. P., Restrepo, P., Destouni, G., Prieto, C., Rodriguez, J. J., Rodriguez-Mirasol, J., Cordero, T. & Gomez-Gotor, A. (2010) Cost-efficient management of coastal aquifers via recharge with treated wastewater and desalination of brackish groundwater: general framework. *Hydrol. Sci. J.* **55** (7), 1217–1233.

Koutsoyiannis, D. (1996) Study of the operation of reservoirs, *General Outline of the Acheloos River Diversion Project*. Athens: Directorate for Acheloos Diversion Works – Ministry of Environment, Planning and Public Works.

Koutsoyiannis, D., Andreadakis, A., Mavrodimou, A., *et al.* (2008a) National Programme for Water Resources Management and Preservation. *Support on the compilation of the National*

Programme for Water Resources Management and Preservation. Athens: National Technical University of Athens.

Koutsoyiannis, D., Efstratiadis, A., & Mamassis, N. (2001) Appraisal of the surface water potential and its exploitation in the Acheloos river basin and in Thessaly. Ch. 5 of *Study of Hydrosystems, Complementary Study of Environmental Impacts from the Diversion of Acheloos to Thessaly*. Athens: Ministry of Environment, Planning and Public Works.

Koutsoyiannis, D., Zarkadoulas, N., Angelakis, A. N., & Tchobanoglous, G. (2008b) Urban water management in Ancient Greece: Legacies and lessons. *J. Water Resour. Plan. Manag. ASCE*, **134** (1), 45–54.

Koutsoyiannis, D., Makropoulos, C., Langousis, A., Baki, S., Efstratiadis, A., Christofides, A., Karavokiros, G., & Mamassis, N. (2009a) Climate, hydrology, energy, water: recognizing uncertainty and seeking sustainability. *Hydrol. Earth System Sci.* **13**, 247–257,

Koutsoyiannis, D., Montanari, A., Lins, H. F., & Cohn, T. A. (2009b) Climate, hydrology and freshwater: towards an interactive incorporation of hydrological experience into climate research—DISCUSSION of "The implications of projected climate change for freshwater resources and their management". *Hydrol. Sci. J.*, **54** (2), 394–405.

Llamas, R. (2004) *Water and Ethics: Use of Groundwater*. ISBN 92-9220-022-4. Paris: UNESCO.

Leckscheidt, J., & Tjaroko, T. S. (2003) Mini and small hydropower in Europe, development and market potential. *GrIPP-Net News*, 2 (1), 2–5.

Moody, L. F., & Zowski, T. (1969) Hydraulic machinery. Sec. 26, in: C.V. Davis & K. E. Sorensen, eds, *Handbook of Applied Hydraulics* McGraw-Hill, Tokyo.

NIC (United States National Intelligence Council) & EUISS (European Union's Institute for Security Studies) (2010). *Global Governance 2025: At a Critical Juncture* (www.foia.cia.gov/2025/2025_Global_Governance.pdf).

Ottinger, R. & Williams, R. (2002) Renewable energy sources for development. *Environ. Law*, **32**(2), 331–368.

Panda, D. P. & Kumar, A. (2011) Evaluation of an over-used coastal aquifer (Orissa, India) using statistical approaches. *Hydrol. Sci. J.* **56** (4), 486–497.

Reiche, D. & Bechberger, M. (2004) Policy differences in the promotion of renewable energies in the EU member states. *Energy Policy* **32**, 843–849.

Roson, R. & Sartori, M. (2010) *Water Scarcity and Virtual Water Trade in the Mediterranean*, University Ca' Foscari of Venice, Dept. of Economics Research Paper Series No. 08_10 (ssrn.com/abstract=1594709).

Saleth, R. M. (2011) Water scarcity and climatic change in India: need for water demand and supply management. *Hydrol. Sci. J.* **56** (4), 671–686.

Shiklomanov, I. A. & Sokolov, A. A. (1985) Methodological basis of world water balance investigation and computation. In: A. Van der Beken & A. Herrmann, eds. *New Approaches in Water Balance Computations* (Proceedings of a symposium held during the XVIIIth Assembly of the IUGG at Hamburg, August 1983). Wallingford: IAHS Press, IAHS Publ. 148, 77–82.

Stefanakos, J., (2008) The role of large hydroelectic plants in the energy system of the country (in Greek), *1st Hellenic Conference on Large Dams*, Larisa, 2, 433–440, Hellenic Commission on Large Dams, Technical Chamber of Greece.

Takeuchi, K. & Simonovic, S. P. (1998) Factors controlling the future needs of reservoirs. Sec. 1.3.4 in: K. Takeuchi, M. Hamlin, Z. W. Kundzewicz, D. Rosbjerg, & S. P. Simonovic, eds. *Sustainable Reservoir Development and Management*. Wallingford: IAHS Press, IAHS Publ. 251.

Tharme, R. E., & King, J. M. (1998) *Development of the Building Block Methodology for Instream Flow Assessments and Supporting Research on the Effects of Different Magnitude Flows on Riverine Ecosystems*, Water Research Commission in Rivers for Life, Postel and Richer, Cape Town, South Africa.

Tiwari, V.M., Wahr, J. & Swenson, S. (2009) Dwindling groundwater resources in northern India from satellite gravity observations. *Geophys. Res. Lett.* **36**, L18401, doi:10.1029/2009 GL 039401.

UNICEF and WHO (2004) *Meeting the MDG Drinking Water and Sanitation Target*, WHO/UNICEF.

Vörösmarty, C. J., Lévêque, C., & Revenga, C. (Lead Authors) (2005), Fresh Water. Ch. 7 in: R. M. Hassan, R. Scholes, & N. Ash, eds. *Ecosystems and Human Well-being: Current State and Trends* Millennium Ecosystem Assessment, USA.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Reidy Liermann, C., & Davies, P. M. (2010) Global threats to human water security and river biodiversity. *Nature* **467**, 555–561.