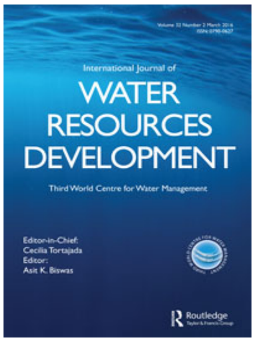

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Water megaprojects in deserts and drylands

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Water megaprojects reconfigure the conception and use of desert landscapes. Driven by limited water resources, increasing demand and growing populations, projects are framed by statements of water delivered, end-users served and local benefits. Decision-making processes, socio-economic costs and environmental implications receive less attention. Research examines the motivations involved and evaluates the challenges of water megaprojects in deserts, including the Great Manmade River (Libya), the South-to-North Water Transfer Scheme (China), the Central Arizona Project (United States) and the Greater Anatolia Project (Turkey), and assesses related projects exemplifying the diversity of water projects in drylands. Their viability and efficacy depends on human motivations and interpretations.

Keywords: water; deserts; megaprojects; Great Manmade River; South-to-North Water Transfer Scheme

Introduction

Throughout history water has defined the desert world. Previously most development of water in arid regions focused on the ability to find and use water locally; more recently technological advances have greatly increased our ability to find, extract and deliver water over extended distances with Los Angeles, USA, being a classic example (Reisner, 1986). Efforts are driven by water need, engineering skills and the financial capacity to reshape the water environment and resources. This has powered urbanization, industry and development, led to social and environmental change, and become part of national action plans and state building (Kuwairi, 2006). In the recent past schemes promoted 'man over nature', 'conquer the virgin lands' and 'westward expansion' across arid regions, steppes and prairies driven by 'new' groundwater resources. The mantra has shifted to economic progress, water security, anti-desertification efforts and the idea of deserts as environments to be managed by expanding populations. This has led to today's era of megaprojects where basic water needs and desires have exponentially expanded with technology and funding to 'bring the resource to the people' rather than situating people 'where the water is'. Deserts and semi-deserts, home to 2 billion people and covering about 40% of the Earth (Middleton, Stringer, Goudie, & Thomas, 2011), are the clearest manifestation of this trend. As ever-greater water is needed for agriculture, industry and domestic use in drylands, megaprojects give short-term solutions, satisfy current demand and offer political expediency. However, megaprojects are often of questionable renewability, sustainability and cost-effectiveness (Alqadi & Kumar, 2014; Hanemann, 2002). They proceed as national expressions of power and capacity and to promote development, social stability and economic growth (Liu & Yang, 2012). Equally, they may result in failed

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ambition and planning, trans-border conflict, exhaust supply and lead to myriad unexpected consequences.

A focus on desert environments encapsulates the how water resources are (mis)used in today's globalized world. The low precipitation and high evapotranspiration rates in drylands limit water resources and contribute to demand for water megaprojects. Three processes stand out: taking groundwater from deserts to serve distant populations and demand, bringing water from wetter regions to dryland centres, and development of resources for local consumption in arid zones. The need for water drives megaprojects that are often viewed as the 'only' option (Alqadi & Kumar, 2014). Water megaprojects vary from the massive Great Manmade River project in Libya, which brings ancient fossil water from deep in the Sahara to the Mediterranean coast, to China's US$77 billion 'South-to-North' Water Transfer Scheme that involves 4300 km of canals and pipelines (Liu & Yang, 2012). Relatively more modest, the United States' Central Arizona Project (CAP) diverts water from the Colorado River to grow water-intensive cotton in the greater Phoenix region that receives 102 mm of precipitation a year (Pierce, 2011). Smaller scale dams, diversions and groundwater extraction provide cities and communities in drylands with essential water for survival from Israel to Uzbekistan, northern Mexico, South Africa and Australia. Water dynamics are measurable and quantifiable; less well understood and appreciated is the impact of desert water projects at their point of origin and locus of consumption. Questions about megaprojects and their stated objectives and outcomes abound. As water is diverted, so can projects' original intent be redirected for other uses, constituencies and advantages. Beneficiaries from water projects vary greatly – from marginal farmers and urban poor to vested elites, industrial champions, governments and national capitals. This paper examines water megaprojects to assess their implications in dryland societies.

Megaproject background

Globally, very dry areas have more than doubled since the 1970s. (IPCC, 2007, p. 3).

The importance of water in deserts (arid regions) and semi-deserts (semi-arid zones), commonly referred to as drylands, is due to their extent, diversity and population (Reynolds et al., 2007). The most populous countries feature vast deserts; drylands comprise 52% of China, 69% of India and 40% of the United States (more than 50% excepting Alaska) and exemplify the range of desert countries and dynamics. Deserts and semi-deserts are defined by the aridity index (AI), the ratio of mean annual precipitation/mean annual evapotranspiration ($AI = \text{arid} < 0.2$, $\text{semi-arid} < 0.5$) and Meigs (1953) 250/500 mm precipitation levels (Maestre, Salguero-Gómez, & Quero, 2012). The long history of developing water in the desert arcs from the Mesopotamians, Egyptians and Romans to today's global pursuit regardless of location or biome. Extracting water has intensified in the last century as nations realized the ability and importance of moving water great distances to satisfy real and imagined demand.

Deserts present a modern-day 'last frontier' for dryland nations. Changes in climate, development, politics and desertification present volatile dynamics as states seek productive lands for expanding populations, extending political jurisdiction and resource extraction. An optimistic view would argue that a major government role is to provide basic water needs (as a public good) to populations, yet globally 2 billion people lack adequate water and the Millennium Challenge Goal of increasing water access to the 40% of the world without access by 2015 will be unmet. A negative interpretation would assert that government and private concerns support water projects to satisfy their own agendas be they control, profit, power or electoral needs. The substantial difference in water development and infrastructure in the global North versus the global South (results of government effectiveness, funding levels) reflects shared perceptions of water as an essential public good, but different ability and methods of implementation. At the core is the need for water to satisfy expanding populations in arid and semi-arid areas, increased land conversion to marginal cultivation, urbanization, shifting human use patterns and significant resource extraction in deserts (Yan, Liu, Huang, Tao, & Cao, 2009). None of these is possible without water.

In the United States, Los Angeles' (California) epic search for water has been well documented and immortalized in films and books for its scale, scope and manipulations that led to a sprawling conurbation of more than 17 million people. This involved acquiring vast water rights and set a standard, for better or worse, for the lengths arid cities may go to in pursuit of water (Table 1) (Reisner, 1986). Yet it is but one of numerous examples. Water flows uphill to Mexico City and Johannesburg and through deserts in India and Saudi Arabia. The Soviets used engineering skills to divert the Amu and Syr Dayra rivers in Central Asia, which showed the potential benefit and damage water projects can cause, from expanding agriculture to the drying of the Aral Sea.

The motivations for megaprojects are framed by assertions of potential water delivered, populations served and economic benefits. Schemes start with perceived physical water shortfalls for present needs or planned future development. Alternatives in water sources, demand, use and management are seldom featured. Proponents assert public good, benefits for agriculture, industry, jobs and greater development. At the same time political and economic forces have vested interests in the construction, routing, financing and water end-use. Recent projects in the United States – Los Angeles, the CAP – are borne of economic opportunity as regional authorities believed that greater water access would attract industry, people and growth. China's South-to-North Water Transfer Scheme aims to satisfy rural and urban interests but remains a government-driven initiative to maintain Beijing's pre-eminence. Libya's Great Manmade River is a self-aggrandizing government project set in place by Colonel Gaddafi to show national power as much as the need for agricultural water in the coastal region. The scale, cost and rights

Table 1. Dryland megacities with principal water sources.

City	Population (millions)[a]	Water source	Source
Delhi	24	Surface	Distant
Metropolitan Area of Mexico Valley	23.8	Ground, surface	Distant
Karachi	22.7	Surface	Distant
Beijing	19.3	Surface, ground, desalination	Distant
Los Angeles	17.2	Surface	Distant
Cairo	16.1	Surface	Local
Tehran	13.3	Surface	Distant
Lima	9.65	Surface	Distant
Lahore	9.5	Surface	Local
Johannesburg	8.55	Surface	Distant
Santiago	6.8	Surface	Local
Dallas	6.65	Surface	Distant
Baghdad	6.55	Surface	Local
Riyadh	6.15	Desalinization, groundwater	Distant
Khartoum	5.3	Surface	Local
Phoenix	4.3	Surface	Distant

Source: [a]Population (Brinkhoff, 2014).

needed are great; thus the state and stakeholders with access to decision-making processes are at the centre of megaprojects.

Planning, execution and impact vary between nations as motivation and demand and usage differ markedly amongst richer and poorer countries. Globally 91% of water goes to agriculture, 5% to industry and 4% to domestic use (Ouda, 2014). However, this masks differences based on dryland development levels. India, Uzbekistan, Egypt and Saudi Arabia use about 90% of water resources for agriculture, China uses 64%, Australia, Israel and South Africa about 55%, the United States 40%, whilst in precipitation-rich Britain just 3% is used for cultivation (Aquastat, 2014).

Megaprojects

Megaprojects are large-scale infrastructure projects involving substantial cost, engineering skill and labour to deliver significant amounts of water and related benefits. Motivated by perceived demand for domestic, agricultural and industrial supply, political agendas, development goals and economic drivers megaprojects involve significant investment, have socio-economic and environmental implications and long timeframes from planning to completion. Megaprojects focus on water transfer schemes, dams, diversions and more recently desalination; here projects from four diverse regions are highlighted (Table 2).

Great Manmade River

Started in 1984, Libya's Great Manmade River project has epitomized global efforts to extract water from deserts. The idea of taking water from the depths of the Sahara to the Mediterranean coast is at first hard to comprehend in a lightly populated country. Understanding that Northern Africa sits atop the world's largest aquifer, and that Libya has greater estimated groundwater reserves than any other country on the continent, begins to explain the project (MacDonald, Bonsor, Dochartaigh, & Taylor, 2012). Four thousand kilometres of pipelines and US$25 billion has redistributed fossil water (35,000–70,000 years old) from empty southern Libya to the coastal region (Mansor & Toriman, 2011) (Figure 1). The project was designed to provide water for agriculture and development in

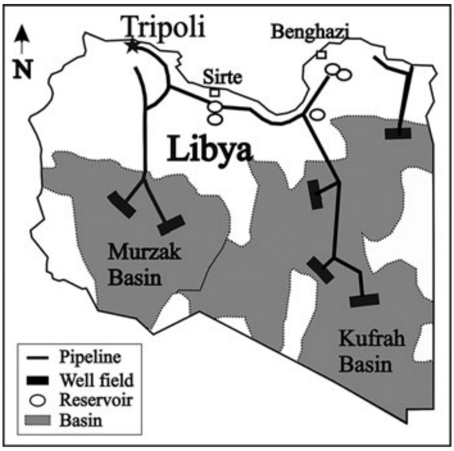

Figure 1. Diagram of the Great Manmade River project in Libya. Source: Danmichaelo (2011).

Table 2. Typology of selected water megaprojects.

Megaproject	Great Manmade River	South-to-North	Central Arizona Project (CAP)	Southeastern Greater Anatolia Project (GAP)
Country	Libya	China	United States	Turkey
Cost (US$ billions)	25	77	5	32
Source	Aquifer	Yangtze, Han	Colorado	Tigris, Euphrates
Water volume/year (billion m^3)	6.5	45	1.85	52.9
Supply region	Sahara	Central/South	South-western USA	Eastern Turkey
Infrastructure	Pipeline	Canal	Canal dam, diversion	
Politics at initiation	Autocratic	Autocratic	Democracy	Military/democracy
Conflict	–	Urban versus rural South versus North Domestic	Agriculture versus urban Canal versus groundwater Domestic	Upstream versus downstream Turkey, Syria/Iraq, Kurds International

Sources: Alker (2008); Liu and Yang (2012); Hanemann (2002); Berkun (2010).

Libya's populated northern region. It also acknowledged problems with seawater intrusion and deterioration of coastal aquifers due to over-extraction (Alker, 2008; Elhassadi, 2007). Original estimates were for the transport of more than 6 million m^3 of fossil water a day to the north, with 70% of this to be used for agriculture (Kuwairi, 2006). Former leader Colonel Qaddafi claimed this would provide water for 4625 years though scientific assessments place this at fewer than 100 years (Scholl, 2012).

Libya's aridity is reflected in just 5% of the country receiving more than 100 mm of precipitation and high evaporation rates that range from 1700 to 6000 mm annually (Kuwairi, 2006). As groundwater accounts for 96% of supply recharge (500 million m^3/year) it fails to meet increasing consumption (4.7 billion m^3/year). Libya, with a best estimate of 99.5 million m^3 of groundwater storage and a potential range up to 234 million m^3 for its population of 6 million people, has sufficient water for current needs (MacDonald et al., 2012). The challenge has been redistributing water from internal basins such as Kufra, Ghadames and Sirt to meet demand; this has required 1300 wells, storage reservoirs, massive infrastructure and energy to develop the multi-stage project (Mansor & Toriman, 2011).

The result has been a dramatic and costly reorientation of water in Libya. Issues include evapotranspiration at reservoirs, resource depletion and subsidence, and a lack of potable water as desalination remains the main source of drinking water (Mansor & Toriman, 2011). At initiation the cost per m^3 was considered to be less than the alternatives, primarily desalination. Evaluation of the project since water first reached Tripoli in 1996 finds mixed results. Since the first water reached Tripoli in 1996 the effectiveness of the project has been questioned. The water was to be used to irrigate 130,000 hectares of new cultivation in the desert and lead to export cropping. In fact, Alker (2008) identifies that the majority of the water is being used for domestic and industrial purposes, whilst groundwater levels have fallen in neighbouring Egypt and Chad. Recent surveys indicate that desalination remains the main source for potable water on the Benghazi plain (Mansor & Toriman, 2011).

The increase in availability has been a driver of migration to coastal regions for jobs and potential economic opportunity. Municipal and irrigation water loses of more than 20%, an abundance of centre-pivot green circles in the desert, high evapotranspiration, and government instability make the long-term outcome and cost-effectiveness of the Great Manmade River uncertain. Water availability (6.5 billion m^3/year) is projected to meet just half of demand by 2025 (Alker, 2008). Further, damage to the project from the country's 2011 civil war (including NATO bombing) has not been rectified. Since the establishment of the post-Gaddafi government data are unavailable, so the current status of water use is unclear. Indeed, the Great Manmade River webpage still features a picture of Gaddafi (www.great-man-made-river.algaddafi.org/great-man-made-river-gmmr-announcements).

South-to-North Water Transfer Scheme

As in many aspects, China presents a unique case. Its per capita water availability is 25% the global average yet water consumption per unit of gross domestic product (GDP) is six times that of the United States (Cheng, Hu, & Zhao, 2009). According to the land ministry, 90% of China's groundwater is polluted and 75% of urban rivers are unfit for human use (Economy, 2007; Qiu, 2010). Much of this results from policy and governance that allows and encourages a water-intensive industrial structure, outdated technologies in some cases, and low water use efficiency (Liu & Yang, 2012); coal processing for power generation alone is estimated to consume one-sixth of China's water. Further, 60% of China's agriculture is produced in the dry North China Plains though the region has 12% of the country's freshwater (Li, 2012). Against this background China has promoted the South-to-North Water Transfer Scheme to bring water to Beijing, a city that has recently been experiencing semi-arid conditions (Pernet-Coudrier, Qi, Liu, Müller, & Berg, 2012). The 4350 km of pipes and canals are claimed to be the world's largest and longest water diversion project. The annual water transfer of 45 billion m^3 will come at a cost of US$77 billion, part of China's US$635 billion, 10-year water development plan (Liu & Yang, 2012).

The project transfers water from wetter Central and Southern China, including the Yangtze River Basin, to transfer to the drier, arid North. The focus is on the capital Beijing, which sits near the edge of the Gobi Desert. Beyond the tourist image of Beijing is a city that shares a water scarcity rate with Saudi Arabia – about 119 m^3 per capita, 1/59th the global average (Hubacek, Guan, Barrett, & Wiedmann, 2009). Tests at observation wells in the city identify the water table dropping up to 6 m a year (Yang, Kang, & Zhang, 2009). Whilst the project is sold as 'borrowing a little water from the south to give to the north' (Mao's description) (Yang & Zehnder, 2005), in fact pipeline plans end in Beijing (Figure 2). The focus is on supply to reduce water insecurity in North China yet the Yangtze River, source of much of the transferred water, receives 40% of China's wastewater upstream of the canal's intake (Economy, 2007). Drought at source points, possible water contamination and lack of demand have been reported. The challenges the project faces – supply, quality, costs – question the viability of the project. However, the project engineer states, 'the negative impacts are so small they almost don't exist' (Kuo, 2014).

Resources are further complicated by climate and the environment. Efforts to divert the Brahmaputra over the Western route involves moving water at 3000–5000 masl

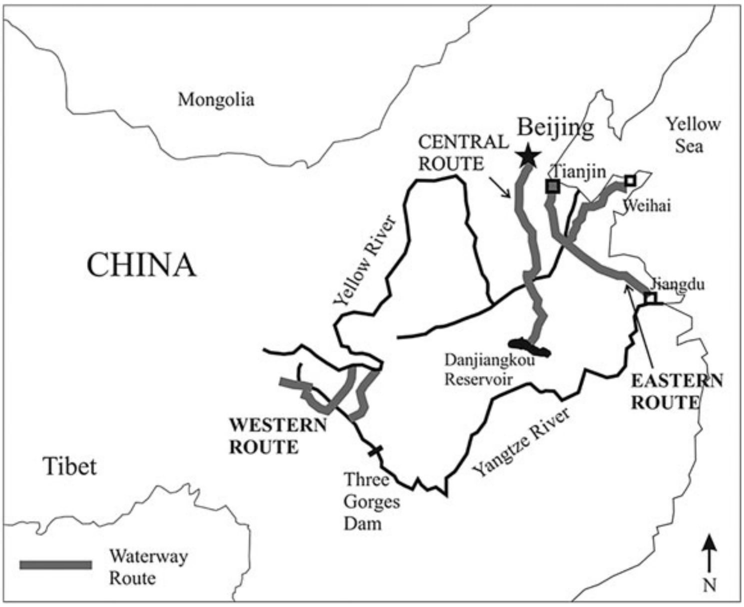

Figure 2. Three routes of the South-to-North Water Transfer Scheme, China. Source: Tsering (2011).

across the Tibetan Plateau to the Yellow River. In 2011 China experienced extreme drought at levels unseen in the Communist era as parts of the Yangtze became unnavigable and hydropower generation was lost (Sternberg, 2012). The anti-desertification 'Great Green Wall' programme planting 56 billion trees in Northern China requires vast water (Wang, Zheng, & Pan, 2012). Internal competition for water resources exists between levels of government – central, provincial, local – and users. Well-funded industries and those deemed essential, such as power generation, receive greater water allotments. These compete with cities and the hundreds of millions of farmers who need a modicum of water to survive, and who, if dissatisfied, the government fears may cause social instability. Before its completion the sustainability and cost-effectiveness of the South-to-North project is uncertain.

Central Arizona Project (CAP)

Completed in 1992, the US$5 billion CAP provides insight into a project that was designed and promoted as the only way to continue agriculture in the Arizona portion of the south-western US desert (Pierce, 2011). Because of the time since inception and open governance, the project dynamics are well documented; the results exemplify how the challenges of water transfer projects are as much socio-economic as physical. The case reflects the political role and 'group think' that pushed the project, economic justification based on flawed demand and cost projections as well as the end-users' ability to select other water supply options (Hanemann, 2002). The result was a costly, inefficient process and outcome that has taken decades longer than projected to both maximize use and repay construction costs.

As the largest and most expensive water transfer project in US history, the CAP was designed to provide irrigation water to Phoenix, Tucson (Arizona) and surrounding areas where average annual precipitation is 102 mm and temperature is 25°C (Figure 3). The project was conceived in the 1920s with planning starting after the Second World War for water to be diverted from the Colorado River. Legal battles with California over water

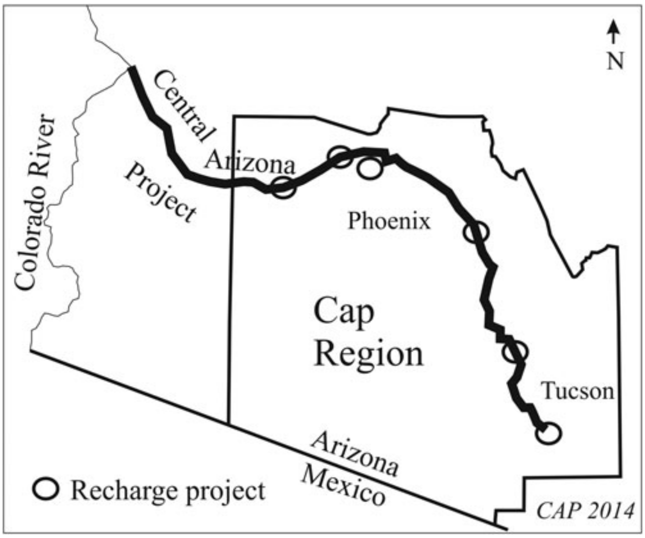

Figure 3. Central Arizona Project (CAP). Source: Central Arizona Project (2014).

rights were not resolved until 1963; construction began in 1973 and was completed in 1992 (Hanemann, 2002). The motivation was economic with farmers and politicians eager to have access to water beyond existing groundwater (Pierce, 2011). However, the project fixated on the symbolism of water in the desert rather than demand and cost. The promoters, including the US Bureau of Reclamation, farming groups and vested political and economic interests, focused on farmers' 'ability to pay' rather than on their willingness to pay as groundwater remained a less expensive alternative. Early external assessment that identified the CAP as costing far more than groundwater was ignored though later found to be true (Young & Martin, 1967).

Other forces, including falling cotton harvests, increased bank lending rates to farmers and economic decline contributed to a significant reduction in acreage planted and halved water demand in two years (1989–91). The result was CAP's underutilization, reduced prices so as to be competitive with groundwater and a push for urban areas to take water at much higher rates. The long process reflected a preoccupation with supply rather than with demand, overoptimistic projections, a failure to acknowledge farmers' individual decision-making ability based on profit rather than on water, neglect of agricultural markets and incorrect assumptions (Hanemann, 2002).

As an engineering project the CAP was a success, yet it was an economic and financial failure (Hanemann, 2002). Irrigation fees were unable to cover the investment and several agricultural water districts went bankrupt, leaving urban areas and taxpayers, rather than agricultural concerns, responsible for the debt, which is scheduled to be paid off by 2046 (Central Arizona Project, 2012). The CAP project became a negative feedback loop of high costs leading to low demand and increased unit costs. What farmers wanted (and got) was access to water provided by CAP in addition to groundwater, a situation much different and more flexible than transferring water where no viable alternative exists. In Arizona the 'problem and solution were [*sic*] far more man-made problems of ownership, management and transfer of water than nature-made problems of scant and declining supplies' (Kelso, Martin, & Mack, 1973, p. 257).

Southeastern Anatolia Project (GAP)

Turkey's GAP is a massive US$32 billion water, energy and development project designed to improve economic conditions and quality of life, enhance investment and infrastructure, generate electricity, create job opportunities, and raise regional living standards (Akpınar & Kaygusuz, 2012) (Figure 4). It does this through a series of dams and reservoirs on the Tigris and Euphrates rivers that have doubled the country's area under irrigation and increased Turkey's hydropower by one-third (Kankal, Bayram, Uzlu, & Satilmiş, 2014). The project has had a major development role for the region's restive Kurdish population, reflecting GAP's economic and political aims in semi-arid south-eastern Turkey (Jongerden, 2010).

The GAP project is a potent example of the transboundary nature of watersheds and water projects. The Tigris and Euphrates are principal water sources for both Syria and Iraq that combined account for 66% of the river basin and 40% of the irrigated cropland (Berkun, 2010). As a regional power, the largest tripartite riparian country and home to the source rivers Turkey has constructed dams and appropriated water, a contentious point of political and economic conflict with Syria and Iraq downstream (Jongerden, 2010). The argument is framed in terms of water shortage as well as water use: per capita Turkey has 1481 m^3 annually whilst Syria has 2362 m^3 and Iraq 5192 m^3 per person (Berkun, 2010; Kankal et al., 2014). Conditions have changed markedly in the region since the project's

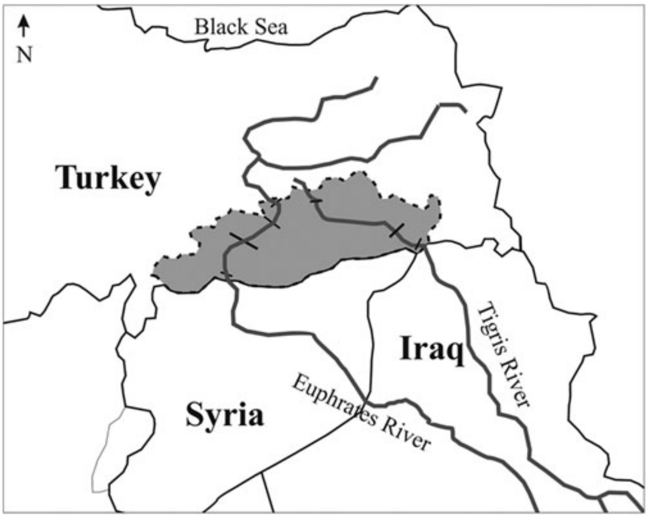

Figure 4. Map of the GAP project (shaded area) with major dam locations. Source: Harris (2009).

inception in 1936 and initial construction in 1960 with importance exacerbated by growing populations, economic pressures, and recently region war and post-conflict states (Akpınar & Kaygusuz, 2012).

Whilst Ataturk Dam, the largest, was finished in 1992, the project is not due to be completed until 2040, reflecting the great cost and construction challenges posed by mega-water projects. The more than 20-year history of the GAP project provides a perspective on the megaproject. Environmental impacts are framed by ground salinization, erosion, reduced land quality and productivity, deforestation, industrialization, and local climatic changes. Social implications include urban development, pollution and sanitation issues, migration and a 3% population growth rate (Berkun, 2012). The government's projected 445% increase in gross national product (GNP), 3.5 million new jobs and 200% increase in per capita income has not materialized. Instead, over 15 years a 2% increase in GNP was realized (Berkun, 2012).

GAP has had clear benefits in water access, irrigation, electricity generation, infrastructure and regional development. Results are mixed for agriculture as harvests increased and production methods were modernized yet degradation occurred (Akpınar & Kaygusuz, 2012). Village welfare and water access improved and women's work decreased significantly (Miyata & Fujii, 2007). Tribal relations and hierarchies have shifted to greater equality as irrigation systems are shared and benefits spread. At a more global agenda Turkey stresses the reduction in greenhouse gasses resulting from increased hydropower generation.

Representative water projects

The Great Manmade River, South-to-North Water Transfer Scheme, CAP and GAP are examples of water megaprojects in arid and semi-arid environments. There are several other versions of large water projects, transfer schemes, and dams in place and planned across global drylands. The following cases include a city, two regions, one dam, a water transfer and one sea; because the projects differ in size, approach, context and effectiveness they are not directly comparable. Though different from conventional water schemes, desalination is included as it is capital and energy intensive and a potential major source of water. Though the scale, intent, cost and beneficiaries of the examples vary, they represent dynamics that drive water projects.

Los Angeles, USA

The city provides the best documented use and abuse of water in a desert. The long history of megaprojects include the Los Angeles Aqueduct, the Colorado River Aqueduct and the California State Water Project that bring water hundreds of kilometres to the city (Reisner, 1986). Water and infrastructure rights precipitated major conflict and legal battles with other districts, regions and states that contested the city's claims. In the century since first transporting water, the city's interaction has changed dramatically and reflects climatic, regulatory and political shifts; however, there remain significant financial and institutional barriers to Los Angeles' water independence (Hughes, Pincetl, & Boone, 2013). Massive water transfer enabled the desert city to expand to 17 million residents and is a case study in both negative and positive aspects of water projects with the city's dynamism, wealth and importance dependent on a continued water supply. Los Angeles has learned to transform its water management and reduce its water consumption by 20% since 1990 (Hughes et al., 2013) despite adding 5 million new residents. This is essential as California has experienced extreme droughts in 2013–14.

Metropolitan Area of Mexico Valley

As one of the largest and highest (2240 masl) urban centres in the world the Metropolitan Area of Mexico Valley (which includes Mexico City) depends on groundwater and external sources that are piped over 150 km and up a more than 1200 m gradient (UNESCO, 2006). Situated in a large valley, the metropolitan area has been importing water since the 1940s and has attempted to increase efficiency, reduce demand and improve recycling. However, the antiquated system (dating to 1789) cannot keep up with a doubling of the population since 1990 as parts of the city exceed 13,500 people/km^2 (Tortajada, 2006). The result is costly formal and informal water markets and a 40% water loss to faulty infrastructure and illegal sales (Human Development Report 2006, 2006). Pipelines cross hills surrounding 5000 m peaks that ring the city, yet there is a question of long-term water supply. Conditions are exacerbated and driven by socio-environmental transformations, periodic earthquakes, hurricanes, floods, drought and now climate change (Romero-Lankao, 2010). It is an example of a water system shaped by the World Bank's water privatization drive in the 1980s where profitable water markets, leaky pipes, inadequate leadership and a lack of motivation to change the status quo threaten the city's supply (Hollander, 2014). Long-term integrated management, including development, industry, migration, the environment and health, is essential for the city's future viability (Tortajada, 2006).

Aral Sea

Fed by the Syr and Amu Dayra rivers from the Pamir Mountains of Central Asia, in 1960 the Aral Sea was the fourth largest lake in the world (Columbia, 2007; Heintz, 2010). During the period of the Soviet Union vast amounts of water were diverted for agriculture, primarily cotton, in arid regions, primarily along the rivers in Uzbekistan and

Turkmenistan. Due to massive over-extraction in a short time span the Aral Sea shrank to one-tenth its original size and was identified as 'one of the world's worst environmental disasters' (Micklin, 2010; United Nations (UN), 2010). Implications ranged from extreme salinity (20-fold increase), chemical pollution, dust storms up to 300 km wide, desiccation-driven changes in climate, and decreased lake surface (−60%) and volume (−80%) (Columbia, 2007; Micklin, 2010; Small, Giorgi, Sloan, & Hostetler, 2001). The region has encountered several challenges, including the drying of the lake and health issues (cancer, tuberculosis), poverty, lack of drinking water and a collapse of the fishing industry. Drivers include water diversion upstream, its role as a drainage basin, Soviet-era policies and programmes, the result of post-independence transition, and ongoing planning and practices. Current research identifies little, if any, chance for the Aral Sea's rehabilitation as multiple stakeholders continue to maximize water use (Micklin, 2010).

Kenya's Turkana region

Potentially large reserves of fossil groundwater reserves have recently been identified in Kenya's northern Turkana region (UNESCO, 2013). As an arid zone experiencing repeated drought events and with an increasing population (2.7% annually), new sources of water have generated much interest. The water was the result of international collaboration including the United Nations, the governments of Kenya and Japan, and the work of a for-profit private company. The findings highlight the potential of satellite mapping techniques to exploit the unique characteristics of desert landscapes – particularly the lack of vegetation to block radar penetration – to explore potential new groundwater sources. The assessment of data from space was then confirmed by drilling test wells. At this point the reported findings are promising, even excessive − 3.45 trillion litres of water per year, in perpetuity (Marshall, 2013) – and require further investigation to understand better the reserves and water quality. Interestingly, the finding comes at a time when new oil reserves have also been identified in the Turkana region.

Red-to-Dead Sea Water Transfer

The Jordan River basin is experiencing severe water scarcity in a region where transboundary water management is intertwined with the political dynamics of Israel, Jordan and the Palestinian Authority (Hoff, Bonzi, Joyce, & Tielbörger, 2011). The drying of the Dead Sea, over-extraction and high precipitation variability contribute to a dependence on water transfer and groundwater extraction (Alqadi & Kumar, 2014). The current plan is to convey water from the Red Sea to the Dead Sea to provide regional water through desalination, generate hydropower and encourage cooperation in the Middle East (Glausiusz, 2010). This is in addition to the US$1 billion 325 km pipeline from Amman to the Disi Aquifer (Alqadi & Kumar, 2014).

The Jordan River represents a closed, over-allocated basin indicative of future water stress scenarios (Hoff et al., 2011). Interconnected, transboundary water resources, high agricultural demand and a 50–80% dependence on 'virtual water' are coupled with political, ethnic and religious dynamics reflecting the great complexity of international water basin management. The issue of funding the 177 km, US$10 billion project, apportioning water and decision-making procedures represent the challenges of future water development (Alqadi & Kumar, 2014).

High Aswan Dam

Completed in 1970, the High Aswan Dam has become the ‘most discussed water infrastructure in the world’ (Biswas & Tortajada, 2012, p. 379). Built to control the flow of the River Nile, generate hydropower, expand cultivation, and protect the Nile Delta from floods and drought, the dam’s social, economic, and environmental benefits and negative impacts have been debated at length (Abu-Zeid & El-Shibini, 1997; Bohannon, 2010). The massive engineering effort expanded irrigated cropping areas by 1.9 million hectares, provides 162 km^3 of water storage capacity, generates 10 billion kilowatts (kW) of electricity, and has significantly contributed to Egypt’s economic development and social stability (Abu-Zeid & El-Shibini, 1997; Biswas & Tortajada, 2012). The dam also reduced the Nile’s sediment flow by more than 98%, has led to subsidence, soil compaction and coastal erosion, and contributed to the Nile Delta being identified as one of the three areas most vulnerable to climate change by the Intergovernmental Panel on Climate Change (IPCC) (Bohannon, 2010; Syvitski et al., 2009). Perceptions, both positive (nationally) and negative (internationally), of the Aswan Dam reflect the complexities and challenges of assessing water megaprojects.

Desalination

Desalination represents large-scale investments in water infrastructure that provide a significant water source. With more than 14,000 plants and a capacity of processing 59.9 million m^3/day globally, desalinization is an increasingly common water source in arid coastal regions and as a means to treat brackish water (Mezher, Fath, Abbas, & Khaled, 2011). Technical advances and reduced costs (to less than US\$0.50/m^3) make this a viable alternative in several desert locations, including the Gulf States, the Middle East/North Africa, the United States, China and Australia (Ghaffour, Missimer, & Amy, 2013). Desalination can be considered as an alternative and potentially less costly water source (Mansor & Toriman, 2011). Drawbacks, including intensive energy use and the resultant greenhouse gas emission and the disposal of both brine and toxic chemicals by-products, add to the challenge and costs of desalination (Mezher et al., 2011). Saudi Arabia, the largest producer of desalinated water, plans to add 1.020 billion m^3/year of capacity with the Shoaiba 3 plant processing 880,000 m^3/day of water; part of a potential 20-year, US $200 billion investment in desalination (Ouda, 2014; Mezher et al., 2011). Improved effectiveness, transport and potential renewable energy sources make desalination increasingly competitive with large-scale transfer costs (Ghaffour et al., 2013). Desalination plants, such as Shoaiba 3, are water megaprojects in their own right.

Megaproject issues

Megaprojects are promoted as grand visions to meet present and future objectives and exigencies. Often the emphasis is on is on engineering solutions to perceived water shortages rather than on resolving water challenges, addressing demand or mitigating system waste and loss. The issues may not be water itself but its ability to influence development, political goals or state power. Water, often presented as a basic social good, is part of highly complex systems. There are a series of recurring issues in water megaprojects that focus on physical and human elements (Table 3). Several factors are common to water in most landscapes, yet these are often exacerbated in deserts and drylands due to limited potential alternative water resources.

Table 3. Potential implications of water megaprojects.

Issue	Example	Reference
Transboundary	Kufrah Basin – Libya, Egypt, Sudan	Paillou et al. (2009)
	Nile – Ethiopia, Sudan, Egypt	Yahia (2013)
	Colorado, Rio Grande – United States, Mexico	Maganda (2012)
Salinization, degradation	Southern Africa	Dahan et al. (2008)
	China	Wang and Li (2013)
	Global drylands	D'Odorico, Bhattachan, Davis, Ravi, and Runyan (2013)
Climate, environment	Arab world	Greenwood (2014)
	Global	Dai (2011)
	Intergovernmental Panel on Climate Change (IPCC)	IPCC (2014)
	Global drylands	Maestre et al. (2012)
Population	Global deserts	Middleton et al. (2011)
	Vulnerability	Sietz et al. (2011)
	Dryland inhabitants	Safriel et al. (2005)
Agriculture, development	Agriculture	Fedoroff et al. (2010)
	Dryland development	Reynolds et al. (2007)
	Development paths of drylands	Safriel and Adeel (2008)
	Land use, politics	Orenstein et al. (2011)

Human dynamics have a great impact on water resources, how they are developed and used. These include physical access, migration to water-rich areas, displacement brought on by dams and control of water resources. These factors transition into policy and governance, rights to water, the power to decide and fund water projects, water allocation and control of downstream resources, and potential conflicts. Transboundary water issues reflect physical rather than political boundaries of watersheds, rivers and subsurface sources where the task is coordinating water landscapes with national borders. Expanding populations drive water demand, food production and competition for land and highlight governance challenges in addressing water issues. Dryland inhabitants are predominately located in low-income countries across Africa and Asia where increasing population and marginal livelihoods lead to exposure to climate, economic and health risks (Middleton, Stringer, Goudie, & Thomas, 2011). As national development levels increase, water use shifts away from cultivation to industry and domestic use, a process that gives water great economic value. The expense and control needed for large-scale water projects makes them the remit of governments, whilst at the small scale the individual can take responsibility. Megaprojects, by their great size and cost, not to mention extraction rights, often respond to political drivers.

Arid regions present marginal environments where minor changes in precipitation, temperature and seasonality combine with natural variability to create unpredictable climate dynamics. For surface water sources climate fluctuation has a major impact in moisture availability and evapotranspiration and thus supply for crops and human consumption. Drought exemplifies the challenge of providing water resources in deserts as their slow onset and uncertain intensity and duration make identification and response to drought-induced water shortages difficult. In arid environments mitigation options are limited, resulting in potentially significant impacts. Factors contributing to snow and glacial melt, such as global warming, directly affect stream and river flow and flood regimes for rivers in drylands. Salinization, erosion, degradation and changing land-use patterns further stress dryland communities.

Water planning focuses on perceived near-term demand and need. In addition to significant benefits, megaprojects have a range of long-term environmental, economic, and social impacts and costs. The extended timeframe from project conception to completion (CAP to 2030, GAP to 2040) make future scenarios difficult to forecast. Projects can change the physical environment by reconfiguring landscapes, sediment flow, subsidence, biodiversity and increase vulnerability to climate change. High investment costs consume resources and divert funds from other potential uses; for example developing new projects to increase water resources comprise 4% of the Saudi Arabian budget (Ministry of Finance, Saudi Arabia, 2013). Financing models may be problematic or prove inaccurate, water tariffs can be difficult to rise and demand can fluctuate. The transition of water from agriculture to higher-value economic use in cities reflects a shift in the role of water, urbanization and political power and can contribute to allocation stress (Molle & Berkoff, 2009). Social conceptions of water may evolve with changes in its cost, availability and perceived equality in access. As different groups, from cities to industries to households, compete for limited supply, water demand and dynamics will remain unpredictable.

Discussion

In *Cadillac Desert*, the story of water in Los Angeles, Reisner (1986) comments that ‘water flows uphill towards money’. This encapsulates the importance of water as a key driver for megaprojects. Much is written about plans, numbers and claims for water projects, yet limited direct documentation exists that assesses projects *ex post facto*. Governments claim the amount of water transferred, residents served and hydropower generated but are reluctant to discuss costs (financial, environmental, opportunity forgone), non-engineered solutions (changes in water use, system efficiency, crops grown) and social implications (jobs, revenue, development, political agendas, migration,). Examination of stated water delivery targets, water quality levels, and the planned and unintended consequences of megaprojects would benefit from greater evaluation. In open societies information is available with effort; in less efficient or autocratic systems official claims are often unverifiable.

The end-use and impact of the transferred water is hard to measure. What does the breakdown for ‘agriculture’ mean in the United States, Egypt or India? Does this indicate improvement of smallholder lives or reflect water diversion to grow export crops that may financially benefit connected elites? Figures for project costs, repayment, amounts of water transferred and efficiency versus other sources, such as desalination, are elusive. Benefits from construction, allocation and implementation of megaprojects can be unclear and may accrue to local users, political constituencies or economic interests. This raises the greater question as to the purpose water serves, from being a free or subsidized public good, a rationed resource or a private service. Societies, governments and global institutions have a long record of water projects to evaluate. Data gathered from multiple sources create a nuanced, contradictory view of the viability of water projects and their lasting impact. Transfer schemes face several diverse challenges from water supply and quality (South-to-North canal), need (Great Manmade River), legal rights (Los Angeles), political implications (CAP, Red-to-Dead Sea), cost (most) and the ultimate effectiveness and the ‘what-if’ the megaproject had not been implemented. The questions are global, the answers locally determined.

Water projects create winners – residents and regions who gain access to water, receive economic advantage and improve quality of life – and losers – who benefit little if at all from megaprojects, pay more for an essential good, and lose land and livelihoods to project footprints. Though large in number, marginal groups such as small-scale farmers, pastoralists/livestock raisers and the urban poor may receive little per capita supply vis-à-vis more influential, richer users. Questions of water inequality and access are not figured into megaprojects though a direct result of them.

The need, effectiveness and benefit of megaprojects in drylands may be problematic as the financial, environmental and social costs are unclear. What is stressed are numbers – volume of water moved, people served, cropland irrigated – rather than alternative solutions. This includes reducing demand, minimizing water loss in delivery systems and examining the efficacy of engineered solutions for what are commonly human-driven problems rather than natural shortages. Populations, where cities are located, the power of vested groups, usually related to agriculture, business and politics, the ability to secure water rights and project funding are key drivers of water schemes that often flow towards capital cities and money interests. Changing human use and economic values of water affect conventional approaches to water projects. Appropriate questions are who are served and profit from the water transfer, the full costs – financial, environmental, social – and alternative resolutions such as demand reduction, reducing system loses and appropriate water use, particularly agricultural, in drylands. Science and experience provide a wealth of knowledge on water in society; what is needed is an understanding of water dynamics and brave decision-making based on on-the-ground reality as well as political arid and dryland nations.

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References

Abu-Zeid, M. A., & El-Shibini, F. Z. (1997). Egypt's High Aswan Dam. *International Journal of Water Resources Development*, *13*, 209–218. 10.1080/07900629749836

Akpınar, A., & Kaygusuz, K. (2012). Regional sustainable water and energy development projects: A case of Southeastern Anatolia Project (GAP) in Turkey. *Renewable and Sustainable Energy Reviews*, *16*, 1146–1156. 10.1016/j.rser.2011.11.015

Alker, M. (2008). The Nubian Sandstone Aquifer system. In W. Scheumann & E. Herrfahrdt-Pähle (Eds.), *Conceptualizing cooperation on Africa's transboundary groundwater resources*. German Development Institute.

Alqadi, K. A., & Kumar, L. (2014). Water policy in Jordan. *International Journal of Water Resources Development*, *30*, 322–334. 10.1080/07900627.2013.876234

Aquastat. (2014). FAO's information system on water and agriculture. Retrieved March 12, 2014, from www.fao.org/nr/water/aquastat/dbase/index.stm; www.fao.org/nr/water/aquastat/countries_regions/

Berkun, M. (2010). Hydroelectric potential and environmental effects of multidam hydropower projects in Turkey. *Energy for Sustainable Development*, *14*, 320–329. 10.1016/j.esd.2010.09.003

Biswas, A., & Tortajada, C. (2012). Impacts of the High Aswan Dam. In C. Tortajada, et al. (Eds.), *Impacts of large dams: A gLobaL assessment*. Berlin: Springer-Verlag.

Bohannon, J. (2010). The Nile Delta's sinking future. *Science*, *327*, 1444–1447. 10.1126/science.327.5972.1444

Brinkhoff, T. (2014). Retrieved from www.citypopulation.de/world/Agglomerations.html

Central Arizona Project. (2012). Information brief – board of directors. Agenda number 8. Retrieved March 20, 2014, from www.cap-az.com/index.php/board/strategic-business-plan

Central Arizona Project. (2014). System map. Retrieved November 15, 2014, from www.cap-az.com/index.php/system-map

Cheng, H., Hu, Y., & Zhao, J. (2009). Meeting China's water shortage crisis: Current practices and challenges. *Environmental Science & Technology*, *43*, 240–244. 10.1021/es801934a

Columbia. (2007). *The Aral Sea Crisis*. Retrieved from www.columbia.edu/~tmt2120/the%20future.htm

Dai, A. (2011). Drought under global warming: A review. *Wiley Interdisciplinary Reviews: Climate Change*, *2*, 45–65. 10.1002/wcc.81

Dahan, O., Tatarsky, B., Enzel, Y., Kulls, C., Seely, M., & Benito, G. (2008). Dynamics of flood water infiltration and ground water recharge in hyperarid desert. *Groundwater*, *46*, 450–461.

Danmichaelo. (2011). Great Man Made River schematic EN.svg. Retrieved February 20, 2015, from commons.wikimedia.org/wiki/File:Great_Man_Made_River_schematic_EN.svg

D'Odorico, P., Bhattachan, A., Davis, K. F., Ravi, S., & Runyan, C. W. (2013). Global desertification: Drivers and feedbacks. *Advances in Water Resources*, *51*, 326–344. 10.1016/j.advwatres.2012.01.013

Economy, E. (2007). The great leap backward? The costs of China's environmental crisis. *Foreign Affairs*, *86*, 38–59.

Elhassadi, A. (2007). Libyan national plan to resolve water shortage problem part Ia: Great man-made river (gmmr) project — capital costs as sunk value. *Desalination*, *203*, 47–55. 10.1016/j.desal.2006.05.003

Fedoroff, N. V., Battisti, D. S., Beachy, R. N., Cooper, P. J. M., Fischhoff, D. A., Hodges, C. N., … & Zhu, J. K. (2010). Radically rethinking agriculture for the 21st century. *Science*, *327*, 833.

Ghaffour, N., Missimer, T. M., & Amy, G. L. (2013). Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. *Desalination*, *309*, 197–207. 10.1016/j.desal.2012.10.015

Glausiusz, J. (2010). Environmental science: New life for the dead sea? *Nature*, *464*, 1118–1120. 10.1038/4641118a

Global Water Forum. (2014). Map of the south-north water transfer project China. Retrieved November 2, 2014, from www.globalwaterforum.org/2014/03/04/diverted-opportunity-inequality-and-what-the-south-north-water-transfer-project-really-means-for-china/

Greenwood, S. (2014). Water insecurity, climate change and governance in the Arab world. *Middle East Policy*, *21*, 140–156.

Hanemann, W. (2002). The central Arizona project. In *Working paper 937*. Berkeley: Giannini Foundation of Agricultural Economics/University of California.

Harris, L. M. (2009). States at the limit: Tracing contemporary state-society relations in the borderlands of southeastern Turkey. *European Journal of Turkish Studies. Social Sciences on Contemporary Turkey*, *10*, 2–17.

Heintz, J. (2010). Aral sea almost dried up: UN chief calls it 'shocking disaster'. Retrieved April 4, 2014, from AssociatedPress. www.huffingtonpost.com/2010/04/04/aral-sea-almost-dried-up_n_524697.html#s78458

Hoff, H., Bonzi, C., Joyce, B., & Tielbörger, K. (2011). A water resources planning tool for the Jordan River Basin. *Water*, *3*, 718–736. 10.3390/w3030718

Hollander, K. (2014). Mexico city: Water torture on a grand and ludicrous scale. Retrieved March 28, 2014, from www.theguardian.com/cities/2014/feb/05/mexico-city-water-torture-city-sewage

Hubacek, K., Guan, D., Barrett, J., & Wiedmann, T. (2009). Environmental implications of urbanization and lifestyle change in China: Ecological and water footprints. *Journal of Cleaner Production*, *17*, 1241–1248. 10.1016/j.jclepro.2009.03.011

Hughes, S., Pincetl, S., & Boone, C. (2013). Triple exposure: Regulatory, climatic, and political drivers of water management changes in the city of Los Angeles. *Cities*, *32*, 51–59. 10.1016/j.cities.2013.02.007

Human Development Report 2006. (2006). Beyond scarcity: Power, poverty and the global water crisis. Retrieved November 7, 2014, from hdr.undp.org/sites/default/files/reports/267/hdr06-complete.pdf

IPCC. (2007). Executive summary. Retrieved November 30, 2012, from www.ipcc.ch/pdf/technical-papers/ccw/executive-summary.Pdf

IPCC. (2014). Climate change 2014: Impacts, adaptation, and vulnerability. Retrieved March 23, 2014, from www.ipcc-wg2.gov/AR5/report/

Jongerden, J. (2010). Dams and politics in Turkey: Utilizing water, developing conflict. *Middle East Policy*, *17*, 137–143. 10.1111/j.1475-4967.2010.00432.x

Kankal, M., Bayram, A., Uzlu, E., & Satilmiş, U. (2014). Assessment of hydropower and multi-dam power projects in Turkey. *Renewable Energy*, *68*, 118–133. 10.1016/j.renene.2014.01.031

Kelso, M., Martin, W., & Mack, L. (1973). *Water supplies and economic growth in an arid environment: An Arizona case study*. Tucson: University of Arizona Press.

Kuo, L. (2014). China has launched the largest water-pipeline project in history. Atlantic. Retrieved from www.theatlantic.com/international/archive/2014/03/

Kuwairi, A. (2006). Water mining: The great man-made river, Libya. *Proceedings of the ICE - Civil Engineering*, *159*, 39–43. 10.1680/cien.2006.159.5.39

Li, S. (2012). China's huge investment on water facilities: An effective adaptation to climate change, natural disasters, and food security. *Natural Hazards*, *61*, 473–1475.

Liu, J., & Yang, W. (2012). Water sustainability for China and beyond. *Science*, *337*, 649–650. 10.1126/science.1219471

MacDonald, A. M., Bonsor, H. C., Dochartaigh, B. É. Ó., & Taylor, R. G. (2012). Quantitative maps of groundwater resources in Africa. *Environmental Research Letters*, *7*, 024009, 10.1088/1748-9326/7/2/024009

Maestre, F. T., Salguero-Gómez, R., & Quero, J. L. (2012). It is getting hotter in here: Determining and projecting the impacts of global environmental change on drylands. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*, 3062–3075. 10.1098/rstb.2011.0323

Maganda, C. (2012). Border water culture in theory and practice: Political behavior on the Mexico-US border. *Journal of Political Ecology*, *19*, 81–92.

Mansor, G., & Toriman, M. (2011). The impact of the man-made river project in providing domestic water in Benghazi plain, Libya. *International Journal of Research & Reviews in Applied Sciences*, *9*, 473–477.

Marshall, M. (2013). Vast supplies of groundwater found under Kenya. New Scientist. Retrieved August 12, 2013, from www.sciencedirect.com/science/journal/02624079

Meigs, P. (1953). World distribution of arid and semi-arid Homoclimates. In *UNESCO reviews of research on arid zone hydrology*. Paris: UNESCO.

Mezher, T., Fath, H., Abbas, Z., & Khaled, A. (2011). Techno-economic assessment and environmental impacts of desalination technologies. *Desalination*, *266*, 263–273. 10.1016/j.desal.2010.08.035

Micklin, P. (2010). The past, present, and future Aral Sea. *Lakes & Reservoirs: Research & Management*, *15*, 193–213. 10.1111/j.1440-1770.2010.00437.x

Middleton, N., Stringer, L., Goudie, A., & Thomas, D. (2011). *The forgotten billion*. New York: UNDP.

Ministry of Finance, Saudi Arabia. (2013). Recent economic developments and highlights of fiscal years 1434/1435 (2013) & 1435/1436 (2014). Retrieved November 4, 2014, from www.mof.gov.sa/english/downloadscenter/pages/budget.aspx

Miyata, S., & Fujii, T. (2007). Examining the socioeconomic impacts of irrigation in the Southeast Anatolia region of Turkey. *Agricultural Water Management*, *88*, 247–252. 10.1016/j.agwat.2006.11.001

Molle, F., & Berkoff, J. (2009). Cities vs. agriculture: A review of intersectoral water re-allocation. *Natural Resources Forum*, *33*, 6–18. 10.1111/j.1477-8947.2009.01204.x

Orenstein, D. E., Jiang, L., & Hamburg, S. P. (2011). An elephant in the planning room: Political demography and its influence on sustainable land-use planning in drylands. *Journal of Arid Environments*, *75*, 596–611.

Ouda, O. (2014). Impacts of agricultural policy on irrigation water demand: A case study of Saudi Arabia. *International Journal of Water Resources Development*, *30*, 1–11.

Paillou, P., Schuster, M., Tooth, S., Farr, T., Rosenqvist, A., Lopez, S., & Malezieux, J. M. (2009). Mapping of a major paleodrainage system in eastern Libya using orbital imaging radar: the Kufrah River. *Earth and Planetary Science Letters*, *277*, 327–333.

Pernet-Coudrier, B., Qi, W., Liu, H., Müller, B., & Berg, M. (2012). Sources and pathways of nutrients in the semi-arid region of Beijing–Tianjin, China. *Environmental Science & Technology*, *46*, 5294–5301. 10.1021/es3004415

Pierce, D. (2011). *Sustainable water management in the Southwestern USA: A case study of Phoenix, AZ; and Las Vegas, NV*. Ann Arbor: University of Michigan.

Qiu, J. (2010). China faces up to groundwater crisis. *Nature*, *466*, 308–308. 10.1038/466308a

Reisner, M. (1986). *Cadillac desert: The American West and its disappearing water*. New York: Penguin Books.

Reynolds, J. F., Smith, D. M. S., Lambin, E. F., Turner, B. L., Mortimore, M. M., Batterbury, S. P. J., & … Walker, B. (2007). Global desertification: Building a science for dryland development. *Science*, *316*, 847–851. 10.1126/science.1131634

Romero-Lankao, P. (2010). Water in Mexico City: What will climate change bring to its history of water-related hazards and vulnerabilities? *Environment and Urbanization*, *22*, 157–178. 10.1177/0956247809362636

Safriel, U., & Adeel, Z. (2008). Development paths of drylands: thresholds and sustainability. *Sustainability Science*, *3*, 117–123.

Safriel, U., Adeel, Z., Niemeijer, D., Puigfefabregas, J., White, R., & Lal, R. (2005). Dryland systems. In M. El-Kassas & E. Ezcurra (Eds.), *Millennium ecosystem assessment: Ecosystems and human well-being: Current state and trends* (pp. 623–662). Washington DC: Island Press.

Scholl, A. (2012). Map room: Hidden waters. *World Policy Journal*, *29*, 9–11.

Sietz, D., Lüdeke, M. K., & Walther, C. (2011). Categorisation of typical vulnerability patterns in global drylands. *Global Environmental Change*, *21*, 431–440.

Small, E. E., Giorgi, F., Sloan, L. C., & Hostetler, S. (2001). The effects of desiccation and climatic change on the hydrology of the Aral Sea. *Journal of Climate*, *14*, 300–322. 10.1175/1520-0442(2001)0132

Sternberg, T. (2012). Chinese drought, bread and the Arab Spring. *Applied Geography*, *34*, 519–524. 10.1016/j.apgeog.2012.02.004

Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W. H., Hannon, M. T., Brakenridge, G. R., & … Nicholls, R. J. (2009). Sinking deltas due to human activities. *Nature Geoscience*, *2*, 681–686. 10.1038/ngeo629

Tsering, T. (2011). China plans to divert water on the Tibetan Plateau. Asia Pacific Memo #110. Retrieved February 25, 2015, from: www.asiapacificmemo.ca/china-plans-to-divert-water-on-the-tibetan-plateau

Tortajada, C. (2006). Water management in Mexico city metropolitan area. *International Journal of Water Resources Development*, *22*, 353–376. 10.1080/07900620600671367

UNESCO. (2006). UNESCO and urban water management. Retrieved March 26, 2014, from www.unesco.org/new/en/

UNESCO. (2013). Strategic groundwater reserves found in Northern Kenya. Retrieved March 26, 2014, from www.unesco.org/new/en/media-services/single-view/news/

United Nations (UN). (2010). Shrinking Aral Sea underscores need for urgent action on environment. Retrieved March 30, 2012, from www.un.org/apps/news/story.asp?NewsID=34276#

Wang, W., Zheng, G., & Pan, J. (Eds.). (2012). *China's climate change policies*. Abingdon: Routledge.

Wang, Y., & Li, Y. (2013). Land exploitation resulting in soil salinization in a desert–oasis ecotone. *Catena*, *100*, 50–56.

Yahia, M. (2013). Leaked report sparks disagreement between Egypt and Ethiopia over dam. In *Nature Middle East*. 10.1038/nmiddleeast.2013.99

Yan, H. Q., Liu, J., Huang, H., Tao, B., & Cao, M. (2009). Assessing the consequence of land use change on agricultural productivity in China. *Global and Planetary Change*, *67*, 13–19. 10.1016/j.gloplacha.2008.12.012

Yang, H., & Zehnder, A. J. (2005). The south-north water transfer project in China. *Water International*, *30*, 339–349. 10.1080/02508060508691874

Yang, M., Kang, Y., & Zhang, Q. (2009). Decline of groundwater table in Beijing and recognition of seismic precursory information. *Earthquake Science*, *22*, 301–306. 10.1007/s11589-009-0301-1

Young, R., & Martin, W. (1967). *Modelling production response relations for irrigation water: Review and implications*. Tucson: University of Arizona.