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PERSPECTIVE

Groundwater: sinking cities, urbanisation, global drying, population growth

John E. Pattison[1] and Peter Cooke[2]

Abstract

An examination of a few examples of aquifer use shows the importance and fragility of groundwater, with poor management leading to over-extraction by individuals and authorities producing subsidence – sinking cities. Freshwater is one of our most precious resources and it is rapidly disappearing, leading to global drying. At the same time, the global and urban populations are increasing, with civil unrest increasing due, in part, to freshwater shortages. The increasing global population and global urbanisation are driving an increase in water use, restriction of aquifer recharge and increased aquifer pollution. It is argued that urban population growth with attendant increased water use, combined with climate change and poor management, is significant in water stress. Particular attention must be paid to the effect of rising populations on local water resources, especially groundwater, and the knock-on effect on urban sustainability.

Keywords: groundwater over-extraction, subsidence, infrastructure damage, population growth, urbanisation, urban sustainability.

1 Independent researcher, formerly University of South Australia. Email: jepattison364@gmail.com

2 Independent researcher, formerly University of South Australia. Email: pcooke1000@gmail.com

Introduction

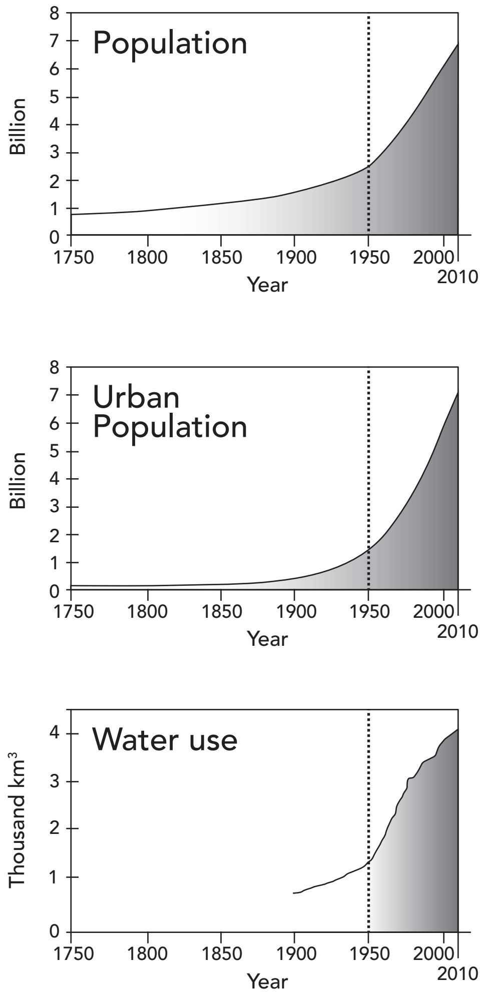
Global warming receives considerable media attention as an urgent major global issue. A visible consequence of global warming is the melting of glaciers and polar ice, resulting in rising sea levels. Consequently, some low-lying islands and coastal communities are threatened with being submerged under the rising sea. Interestingly, there are communities under a similar threat of being submerged owing to a process unrelated to global warming but seldom discussed – some cities are sinking. The reason for this second phenomenon is indisputably related to the increasing number of people in these communities using groundwater from underlying aquifers. Graphs showing the rapid increase in global water use (Figure 1) and the rapid decline in global freshwater resources (Figure 2), at the same time as the global and urban populations are rapidly increasing, communicate a strong message, but do not convey the complexity of the situations that underlie the graphs, particularly in the case of freshwater from aquifers.

There is often mismanagement and indecision leading to problems such as aquifer depletion and sinking cities with damage to civil infrastructure, corruption and civil unrest. Given the increasing global population and global urbanisation driving the increase in water use, the restriction of aquifer recharge and increased aquifer pollution, this article considers whether the global and urban water cycles are sustainable for the current and future populations and how they impinge on urban sustainability. After outlining the nature and importance of groundwater, a few examples of aquifers and their contexts are briefly described. Issues concerning sinking cities, urbanisation, global drying and the difficulty of predicting future populations – global and urban – with any certainty are then considered. It is argued that regional population growth with increased water use, combined with climate change and poor management, is significant in water stress.

Groundwater

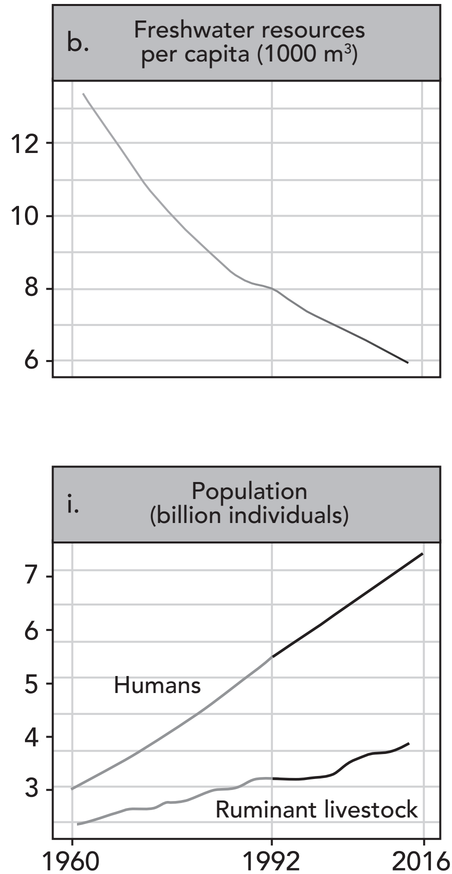
Groundwater is the water found in soil pores, rock formation voids and fractures located beneath the ground surface. A volume of below ground-level, unconsolidated rock is called an aquifer when it can provide a usable quantity of water, while the depth below ground-level at which the soil pores and fractures and voids in the rocks become completely saturated with water is called the water-table. Groundwater is naturally recharged by surface water percolating down from rain, streams and rivers; it may discharge from the ground-surface naturally

Figure 1. Trends from 1750 to 2010 in globally aggregated global and urban populations and of global water use. Water use includes agricultural, domestic and industrial uses



SOURCE: AFTER STEFFEN ET AL. 2015

Figure 2. Trends from 1960 to 2016 in globally aggregated freshwater resources per capita and of global human population



SOURCE: AFTER RIPPLE ET AL. 2017

at springs and seeps. Evaporation can also cause loss of water from an aquifer, especially in arid regions. Groundwater is pumped for agricultural, municipal and industrial purposes by constructing and operating extraction wells, as it is often used for public water supplies because it is cheaper, more convenient and less vulnerable to pollution than surface water. However, if more water is extracted from an aquifer than is going in, it will eventually run out, leading to dire consequences. Groundwater may be polluted by improper disposal of industrial and domestic wastes on land, overuse of agricultural chemicals on farms, dissolving of soluble salts from the rocks through which the water passes, or seawater intrusion. The main pollutant salt is sodium chloride, but others, some hazardous to health, such as those of arsenic (Podgorski and Berg, 2020) and uranium (Riedel and Kubeck, 2018), may also occur. Pollution may also be microbial, particularly with faecal bacteria from septic tanks and crop irrigation with untreated effluent (Ferrer et al., 2020), which may lead to diarrhoea and malnutrition.

Groundwater makes up ~30% of the world's freshwater supply, which is ~0.76% of the world's water; including oceans and permanent ice (WSS, 2018). Groundwater is a valuable resource that can serve as a natural buffer against surface water shortages since its global storage capacity is about equal to the total amount of freshwater frozen in snow and ice, including at the north and south poles. The largest users of groundwater (in 2010) were, in descending order, India, USA, China, Pakistan, Iran, Mexico and Saudi Arabia, which accounted for 74 per cent of global groundwater usage (Berne et al., 2020). The Nubian aquifer in Northern Africa (below most of Egypt and parts of neighbouring Libya, Chad and Sudan) is the largest aquifer system in the world being just over two million square kilometres in area. The Great Artesian Basin in central and eastern Australia extends to almost two million square kilometres, while the Guarani aquifer in central South America (below parts of Argentina, Brazil, Paraguay and Uruguay) covers ~1.2 million square kilometres. By analysing the trace elements in groundwater, hydrologists have determined that water extracted from aquifers may be more than a million years old.

Similar to surface water, aquifers have been over-used and polluted in many places, but their invisibility leads to mismanagement. Aquifer capacity is hard to estimate and water management organisations typically ignore effects that won't materialise during their term of office (three to five years), ignoring the decades or centuries of time delays inherent in groundwater's dynamic response to development. Groundwater extracted from insufficiently recharged aquifers, can severely damage both terrestrial and aquatic ecosystems. Subsidence is the collapse of the ground above when too much water is removed from the underground, decreasing the occupied space below the ground surface. Damage at the surface is exacerbated by the development of large features such as fissures and sinkholes, in addition to uneven settlement. During the collapse, sand and silts may move into the spaces previously occupied by water decreasing the volume of space that water can reoccupy when the aquifer is being recharged. Subsidence, caused by the increasing extraction of groundwater due to growing populations, is a problem globally. A world map of land subsidence has recently been published (Herrera-Garcia et al., 2021) and may be used to visualise the subsidence in any area of interest. It shows that nineteen per cent of the global population, and twelve per cent of the global gross domestic product, face a high probability of subsidence.

The World Health Organization estimates that a healthy person needs between fifty and a hundred litres of freshwater a day, depending on their cultural practices (Reed and Reed, 2013). However, there is a water crisis in many regions of the world, particularly in the poorest regions, and the problems will progressively become global. There are three inter-related crises: safe water access, water quality or pollution and water scarcity, the last being the pre-eminent problem (Lall et al., 2008). There is widespread scientific agreement that population growth and unsustainable consumption are the main drivers of the current growing scarcities of freshwater (Bradshaw et al., 2021; Crist et al., 2022). Freshwater has been a scarce resource historically and conflicts over water go back about 5,000 years (Angelakis et al., 2021). Predictably, severe mismanagement by some cities and countries will cause excessive migration and possibly lead to water wars in the future (Parker, 2016). It is also generally acknowledged that the recent civil unrest in Iran had a water shortage component (Dehghanpisheh, 2018). Even within a single country, different aspects of water resources may be managed by different government agencies, causing internal power conflicts and inefficiencies (e.g. Davies, 2019).

Examples

The following examples will show the complex situations related to regulation of groundwater, and water in general, faced by governments and managers.

Beijing, the capital of China, with a population of more than twenty million, has no major river in its vicinity and rain is unreliable with frequent droughts. Tens of thousands of wells in and around Beijing have dropped the water-table of a large aquifer under Beijing. There are regulations on their use, but they are inconsistently regulated or enforced so that areas of Beijing are sinking 11 centimetres per year (Chen et al., 2016). Total annual water use was 3.6 billion cubic metres, whereas freshwater resources provided only ~3 billion cubic metres before 2015. A South to North Water Diversion canal and tunnel system of 2,400 kilometres from the Hann River was completed in 2015, to bring 45 billion cubic metres of water to Beijing each year to overcome its water shortage (Chen et al., 2020). Simultaneously, plans were announced to phase out 367 wells, and programmes introduced to improve pollution control and treatment, and reduce freshwater use in industries, farms and households. It has been proposed that Beijing be moved further south to more reliable water sources.

Greater Mexico City is built on an ancient lake-bed in a mountain-ringed basin more than 2.1 kilometres above sea level, and has a population of ~20 million. The city requires water at a rate of about 60 cubic metres per second, of which about thirty per cent comes from distant rivers and lakes, and the rest from a vast underground aquifer that is being depleted at a rate faster than it is being replenished (Kahn, 2018). Consequently, the city is sinking at a rate of up to 50 centimetres per year due to groundwater extraction, with surface fissures occurring around the city. For five months every year there is a lot of rain which, instead of recharging the aquifer, runs into a massive drainage system to prevent flooding. As the city now sits ~2 metres below neighbouring Lake Texcoco, flooding has become a major concern. The city has sunk ~9 metres in the last century, and it is estimated that in the next century and a half, sections of the city could drop by as much as ~20 metres and parts outside the city by up to 30 metres (Chaussard et al., 2021). Due to different sections of the city subsiding at different rates the built environment reportedly looks like a surrealist painting with everything appearing twisted and tilted (Simon, 2021). Damage to the metro railway has already caused an accident and more are predicted (Kornei, 2017). Mexico City is also subject to occasional earthquakes. In 1954 pumping was banned in the city centre, but not in the metropolitan areas. The subsidence in the city centre stabilised, but is still a major problem in most parts of the metropolitan areas. Because of damaged water pipes, nearly forty per cent of water is wasted, such that the eastern section of the city has only about an hour of water supply a day during the rainy season and can go dry for months without water during the dry season (Kahn, 2018). The quality of the water is also poor because of contamination from broken sewer pipes. It is more economical and common to use water-carrier tankers to transport the water directly from the aquifer to its place of use. The repair cost is much larger than after a severe earthquake with no end result as the city continues to sink. Mexico City has spent billions of dollars on flood control; however, this has not helped the city's water shortage or sinking problems. Little water is recycled or used to recharge the aquifer.

Jakarta, the Indonesian capital, with a population of ten million, sits on marshy land on the coast of the Java Sea, with thirteen rivers running through it, and is subject to frequent flooding from both the rivers and the sea. The city does not pipe in enough drinkable water, and its rivers are highly polluted, so Jakartans rely largely on wells which extract groundwater from shallow aquifers, leading to subsidence. It is one of the fastest sinking cities in the world (Lin and Hidayat, 2018) and is sinking faster than the sea-level is rising. Areas of north Jakarta, including the seawalls designed to protect them from flooding, are falling ~25 centimetres per year; almost half the city is already below sea level, and some areas could be totally submerged by 2050, notwithstanding the presence of seawalls (Andreas et al., 2018). Other parts of Jakarta are also sinking but at slower rates, varying between 1 and 15 centimetres per year Attempts by the authorities to regulate groundwater extraction have failed; illegal extraction is still common. The problem has been aggravated by the sea level rise due to global warming and the rapid growth of new apartment blocks, shopping centres and government offices which increase the risk of disastrous flooding. Despite heavy monsoonal rain, the rainwater is drained away and does not recharge the aquifer because 97 per cent of the city is covered with concrete and asphalt. The national capital, Jakarta, will relocate to Kalimantan (Indonesian Borneo), according to a statement made by the President Joko Widodo in August 2019 (Lyons, 2019). Nonetheless, Jakarta will remain the financial and commercial hub of the country, and the majority of its residents and industries are expected to remain in Jakarta and will still require freshwater. Unfortunately Jakartans have become complacent and have adopted a fatalistic attitude to the sinking of their city (Lin and Hidayat, 2018).

Manila city, the capital of the Philippines, has a population of nearly two million and is located on relatively flat, low coastal flood plains on the eastern shore of

Manila Bay, Luzon Island. The Greater Manila Area includes the built-up areas and some rural areas around metropolitan Manila and has a population of >28 million. Most of the region has a tropical wet and dry season. In the wet season it rarely rains all day, but heavy rainfall occurs during short periods. The surface reservoirs are too small to store enough of this rain for agriculture, fish ponds and domestic needs during the dry season. The Pasig River flows through the middle of the city to Manila Bay; however, it is reportedly one of the most polluted rivers in the world. Groundwater is extracted from a number of aquifers in the delta plain and is used for drinking by about fifty per cent of the population (Mirano, 2019). Fishponds, a large industry in the coastal areas of Manila Bay, use large volumes of groundwater to replace the water fouled by overfeeding. Due to excessive unregulated groundwater extraction, areas of metropolitan Manilla are sinking at up to 10 centimetres per year (Eco et al., 2020). Areas in metropolitan Manila sunk from 70 centimetres to 135 centimetres over the thirty years from 1979 to 2009. The rise in the sea level due to global warming is estimated to be ~0.3 centimetres per year, making it the lesser problem for coastal communities suffering from subsidence. Manila is exposed to many natural hazards such as earthquakes, floods, landslides, tsunamis and typhoons; it is surrounded by numerous active fault systems, and has been ranked as the second riskiest capital city after Tokyo to live in. Flooding is endemic in the Greater Manila Area because waterways are blocked by human rubbish and volcanic debris, and constricted by structures because of poor building regulations or their implementation (Mirano, 2019). Numerous ground fissures have emerged in areas away from the coast, causing extensive damage to overlying structures. Although neither natural nor man-made land subsidence is yet understood or acknowledged in the Philippines, local, relative sea level increase from these sources can occur far faster than the global sea-level rise (Rodolfo and Siringan, 2006). Work to clean-up the Pasig River commenced in 1989 but was ineffectual with the executive director being dismissed in 2019 for alleged corruption (Gita-Carlos, 2019).

Venice, Italy, is located within the Venetian Lagoon at the northern end of the Adriatic Sea, and is notorious for its regular flooding. Although the residential population of the historic island city was only 53,000 in 2019 (before Covid), and is decreasing, the population of greater Venice (including the neighbouring mainland boroughs and other lagoon islands) in 2019 was 636,000, and is growing (PopStat, 2023). In addition, the annual tourist population in 2019 was 5.523

million and is also increasing (Imboden, 2023). Venice has, since its beginning, obtained freshwater from an underlying coastal aquifer system, as well as by collecting rainwater (Tosi et al., 2014). Before the 1960s, the water extracted from the aquifer had been replenished naturally. However, over-exploitation during the 1960s, especially by an increasing population, lowered the water-table alarmingly. In the 1970s, the authorities closed many wells, and the water-table appeared to stabilise. Freshwater is now mainly supplied by aqueducts from nearby mountains. More accurate measurements in 2012 revealed that Venice is still slowly sinking (Bock et al., 2012) because of two other factors in addition to the compaction of the aquifer. Venice was built on marshland. The buildings sit on top of more than ten million 25-metre-long tree trunks forced into the marshlands to reach the more solid sedimentary clay below, forming pile foundations (Mat, 2020). Although these piles have proven to be excellent for their purpose, they are not perfect and buildings are very slowly subsiding due to their extreme weights. In addition, the Venetian Lagoon sits on the Adriatic tectonic plate that is slowly subducting beneath the Eurasian plate causing everything on it, including Venice, to slowly lose elevation (Devoti et al., 2002). Venice is estimated to be sinking at a combined rate of 1 to 2 millimetres per year, which is substantially less than when groundwater was being extracted (Bock et al., 2012). Nevertheless, apart from a ~110 mm rise in sea level, natural processes and groundwater extraction are believed to have played a part in the estimated 120-millimetre subsidence of Venice throughout the course of the twentieth century. In the next twenty years, the city and surrounding land is estimated to sink by ~80 millimetres relative to the sea. Flooding has been exacerbated by poor management (Mat, 2020). The building of massive flood gates designed to isolate the Venetian Lagoon from the Adriatic Sea was commenced in 2003. The project, however, has been plagued by controversy and political scandal, and has run continually over budget; in 2014, 35 people were arrested, including the mayor and a former governor of the region, in connection to funding irregularities (Harlan and Pitrelli, 2019).

Greater Tehran, capital of Iran, has a population of ~16 million and has a cold semi-arid climate; rainfall is highly seasonal with a short rainy season leaving the land hot and dry for most of the year. Greater Tehran is supplied by surface water from dams, as well as by groundwater (Ravilious, 2018). Tehran’s aquifers have been severely depleted owing to drought, a growing population, urban and industrial development, and irrigation of nearby agricultural land. Because of inefficient practices, a large part of the water used in agriculture is lost via evaporation. Further, the average Tehran resident uses 325 litres of water per day, making domestic water consumption in the country seventy per cent above the global average. Notably, the average groundwater level in Tehran decreased by ~12 metres from 1984 to 2011. A recent study (Haghshenas and Motagh, 2019) found significant subsidence in ~10% of the city centre and in many satellite towns and villages in Tehran's southwestern region: with rates exceeding 25 centimetres per year in the western Tehran Plain, which is a mix of Tehran's urban sprawl, satellite towns and agricultural land, and 22 centimetres per year to the southeast of Tehran city. The effects of Tehran's sinking are seen in uneven streets, shifted curbs, cracks in walls and tilted buildings. In addition, huge fissures, several kilometres long and up to four metres wide and deep, have appeared in the Tehran Plain to the southeast of Tehran – some of these are threatening to collapse power-transmission lines and buckle railway lines. In and around Tehran, there are areas containing about 250,000 houses,120 kilometres of railway lines, 2,300 kilometres of roads, 21 bridges, 30 kilometres of oil pipeline, 200 kilometres of gas pipeline, and 70 kilometres of high-voltage power lines, which have substantial subsidence (Ravilious, 2018). This infrastructure will be badly damaged by Tehran's continuous subsidence unless appropriate groundwater management is put in place. Unfortunately, efforts by the government to control groundwater extraction are failing. Some 30,000 unlawful wells are thought to be still operating throughout Greater Tehran, despite the fact that ~100,000 illegal wells have been shut down in Iran (Ravilious, 2018). Another problem is the pollution of groundwater caused by industrial and municipal wastewater. In the past, the Iranian government's main concern was to prioritise the building of dams (Madani, 2014). However, this approach is no longer appropriate as the total storage capacity behind Iran's dams now exceeds the water potential of its rivers. The government now plans massive investments in seawater desalination. Some analysts believe that the continuing water crisis has been a significant factor in the growing civil unrest in rural areas (Dehghanpisheh, 2018). A decision to move the capital from Tehran was made in 2009, but progress has been very slow (Tait and Hoseiny, 2009).

In addition to the aforementioned examples, many other cities are concerned about their rapidly depleting aquifers, which are or may commence sinking, or may become contaminated by sea water, such as Gaza City and Brasilia.

Gaza City, in the narrow coastal Palestinian Gaza Strip, with a population of ~2 million, has negligible surface water. It relies almost entirely on a large coastal aquifer that stretches along the eastern Mediterranean coast from the northern Sinai Peninsula in Egypt, via the Gaza Strip, into Israel covering an area of 18,370 square kilometres (UNESCWA, 2013). The ground water originates from inland recharging areas and generally flows towards the sea where it discharges. However, the Gaza Strip extracts only ~11 per cent of the total water extracted from the aquifer, with Israel and Egypt taking the greater proportion. Continued over-extraction has led to lowering of the water-table, causing seawater intrusion. Additionally, pollution from untreated sewerage and agricultural return flows has severely impaired water quality, with the UN warning that >97 per cent of Gaza's water is unfit for domestic use (Khatib, 2017): the residents of Gaza have relied upon bottled water for many years (Wade 2023). Reconstruction after the current Hamas-Israeli war ceases will provide an opportunity for the Gazan government to rebuild the water and sanitation systems. Though the problem is exacerbated by sanctions, it shows what happens because of overpopulation and poor management of a limited resource. Unfortunately, due to political constraints there are no formal or informal agreements for the optimum use of the aquifer.

Brasilia, the capital of Brazil, has a population of ~4 million. Water is obtained from dams and the Guarani aquifer beneath Brazil. Decreasing rainfall, low level of dams and rapid and disorderly growth in Brasilia have caused occasional water rationing. It is ironic that Brazil is nearly half the area of South America, with heavy rainfall in the Amazon rainforest, and yet it suffers from occasional droughts. This is primarily due to the deforestation of its rainforest, which has changed the weather pattern in Brazil causing areas to become drought-prone (Perugini et al., 2017). The Amazon River and its tributaries have become polluted with rubbish and sewage in addition to the topsoil washed down from deforested areas (Ribeiro, 2018). Heavy extraction of groundwater continues, especially for irrigation, and is rapidly becoming politicised with its control becoming increasingly controversial.

Discussion

These examples show that each individual situation is complex. Importantly, these cities face many other environmental problems that governments consider more urgent, such as incessant flooding, hurricanes, tornados, earthquakes, volcanic eruptions and the like, all causing damage to infrastructure incurring high repair costs. However, the most important common factor for water sustainability is the increasing populations that require fresh water for domestic, industrial and agricultural uses. Personal and national self-interest is evident, as are mismanagement and possible corruption. Freshwater is wasted on water-hungry crops such as cotton and rice. Due to their invisibility, aquifers are often overused and not replenished because of lack of rain or draining rainwater out through stormwater systems. Better management of freshwater is urgently required in order to avoid further subsidence and civil unrest.

Sinking cities

It is interesting that many coastal cities are experiencing a rate of subsidence, and hence, flooding, which is greater than the rising sea-level due to global warming. Subsidence is a global problem: it reduces aquifer-system storage capacity, causes earth fissures, damages buildings and civil infrastructure, and increases flood susceptibility. The only known method to prevent subsidence is to use less groundwater, and to rely mainly on surface water – a remedy which is extremely difficult to enforce when many people own their own wells. Attempts to recharge aquifers may not be successful and may possibly decrease the volume of the aquifer permanently. Further, natural recharging is a slow process owing to the long time it takes for water to percolate from the ground surface down to the aquifer. In many cases, the immediate needs for freshwater are considered more important by governments than long term sustainability, and it is optimistically hoped that rain will eventually recharge the aquifers and reduce subsidence. An attitude of do nothing and hope that the problem will go away or be tackled by later governments frequently prevails, often resulting in poor management of groundwater (Rodolfo and Siringan, 2006; Diamond, 2011; Dehghanpisheh, 2018; Mat, 2020).

Urbanisation

In 2020, 56.2 per cent of the global population was urbanised and it is predicted that by 2050 about 68 per cent of the developing world and about 86 per cent of the developed world will be urbanised (UNDESA, 2019). The impact of urbanisation on society, the economy and the environment is immense, and it offers the promise of sustainability with more efficient use of resources. Urban population growth is due to three factors: local fertility; international migration, especially from neighbouring countries with internal conflicts; and rural-to-urban migration for those in search for a better quality of life. But unplanned migration into areas often results in the rapid grown of slums and shanty towns and the benefits don't materialise.

It is a general problem that, as cities grow, surface water is often directed to flow away from the city by storm water systems to avoid flooding, while any prior-existing natural drainage channels and swamp-land are drained and built upon so that recharging of aquifers will no longer occur even though there may be sufficient rain. The denser the population, the more problems there are with maintaining the aquifers. Sustainable water drainage and aquifer recharging systems should be planned before urbanisation takes place; if undertaken afterwards to revitalise an area, these often cause preventable social upheaval.

Unfortunately, it is often considered a waste of resources by profit-oriented companies to clean up their pollution, including any that will seep down to an underlying aquifer, unless prosecuted and fined (Lall et al., 2008). A recent study found that urban megaprojects in south-east Asia threaten freshwater justice for local communities (Hawken et al., 2021). They concluded that large scale urban initiatives are typically the opposite of effective urban planning: They negatively affect regional water systems, and their sponsors and funders take little responsibility for these effects. When large sums of money are involved in any major development project, there is always the possibility, or at least a suspicion, of corruption. On the other hand, in a few cases, governments are being reluctantly forced to consider relocating cities due to the shortage of freshwater for their growing populations and increasing damage to their infrastructure. But the old city remains occupied, still requiring freshwater, and may still be sinking.

Some governments are proposing desalination of seawater, but these plants are very expensive to construct and to operate. For example, in 2007 during a severe drought, the South Australian state government decided to build a desalination plant to guarantee the water supply to its state capital city, Adelaide, which has a population of ~1.3 million. A desalination plant with the capacity to provide the city with up to fifty per cent of its drinking water needs, around 1,000 gigalitres per year, was completed in 2012 at a cost of A$1.83 billion. It operated at full capacity for two years at a cost of A$130 million per year. After the drought broke in 2015, the plant has been operating at ten per cent of its capacity to reduce costs (DEW, 2022), showing that even an advanced economy has problems affording the construction and operation of a relatively small desalination plant.

With climate change, many regions of the world will experience more droughts, while, combined with population growth, the ability of local storage infrastructure such as dams and aquifers to buffer the population from the impact of such droughts decreases. As water consumption is increasing, water management becomes a major challenge for governments to provide freshwater at minimal cost and minimal energy consumption in a sustainable way, but is made difficult due to the uncertainties created with climate change, growing populations and ageing infrastructure for water supply requiring maintenance or replacement. (Lezcano et al., 2021). Notwithstanding the hyperbole of some billionaire entrepreneurs, the mining of off-the-Earth bodies, such as asteroids and moons, is unlikely to be financially viable nor is there likely to be any benefit to large-scale environmental, social or economic conditions on Earth (Glester, 2018; Zeisl, 2019).

Subsidence is a growing problem in the developing world as cities increase in population and in water use per capita without adequate pumping regulations and/or enforcement (and with possible corruption). Subsidence is not restricted to urban areas but civil infrastructure is more concentrated there, causing a greater amount of damage.

Global drying

The loss of fresh groundwater adds to the loss of fresh surface water, including polar and mountain ice and snow, receding glaciers and the drying and pollution of freshwater rivers and lakes, producing global drying (Diamond, 2011). The increased extraction of groundwater is probably the reason behind the ongoing rise in water use (Steffen et al., 2015). The loss of surface water will decrease the average albedo of the Earth and cause the exposed ground to absorb more of the Sun's radiation contributing to global warming. There is also a consensus among weather modellers that 'the average global biophysical climate response to complete global deforestation is atmospheric cooling and drying' (Perugini et al., 2017: 1). At the 2018 UNESCO World Water Forum held in Brasilia, it was noted that there are a growing number of cities with freshwater shortages. By 2050, five billion people could have poor access to water. It was forecast that by 2025 the global demand for agriculture will increase by sixty per cent with the water required for this. Agriculture is the dominant water user accounting for seventy per cent of global water use and greater than ninety per cent in arid and semiarid regions. Agricultural water use is very inefficient and often, depending on the watering technique employed, only between ten and twenty per cent of the water supplied is utilised by the plants (Lall et al., 2008). A 2018 report (UNWWDR, 2018) states that 'The global demand for water has been increasing at a rate of ~1%/yr over the past decades as a function of population growth, economic development and changing consumption patterns, and it will continue to grow significantly over the foreseeable future.' It recommends using natural processes to improve water availability, such as soil moisture retention, groundwater recharge, improving water quality, and reducing risks associated with water-related disasters and climate change. Other sources of freshwater, such as desalination, recycling, harvesting fog and collecting icebergs from the polar regions, should be developed (Lisbona, 2021). More efficient methods of freshwater use in agriculture and industry should be adopted, as should sewerage treatment to reclaim water, as well as reducing domestic use of water with water tariffs to provide an incentive to save water. However, the 2018 report has been severely criticised for underplaying the connection between population and economic growth, and water demand (Boretti and Rosa, 2019). The UN, through the IAEA, also mediates the water allocations of users of large multinational aquifers, such as the Nubian aquifer in Northern Africa and the Guarani aquifer in South America, in an attempt to avoid conflicts and to sustainably manage the aquifers (Britain et al., 2015). As aforementioned, there have already been conflicts over access to freshwater and other resources, and more are expected to occur (Nnoko-Mewana, 2018; Ribeiro, 2018; Darling, 2019; Angelakis et al., 2021).

A less commonly known effect of global drying is that it changes the distribution of water stored around the Earth (through glacial ice melting and aquifer depletions), which, in turn, contributes to polar drift (Deng et al., 2021). The points where the Earth's rotational axis passes through the Earth's surface, the north and south poles, are not static but move, as does the equator, changing the global weather distribution pattern. Earth's natural climate change is not unexpected: astronomical factors, such as variations in orbital eccentricity, axial tilt, precession of the Earth's orbit and varying luminosity of the Sun, can change, affecting the Earth's weather patterns. For example, at the end of the last Ice Age the Sahara

Desert in northern Africa was as dry and uninviting as it is today. However, ~11,000 BP, arguably the largest climate change-induced environmental change in the Holocene period occurred, rapidly transforming the Sahara into a lush green savannah in less than 500 years, with forests in the valleys, with groundwater sources, that were occupied by prehistoric humans (Cheddudi, 2021). This transformation was caused by slight cyclic changes in the tilt of the Earth's orbital axis, which in turn caused the intensification and northward expansion of the summer monsoon over northern Africa. During a few millennia of plentiful rain and lush vegetation, and under growing population pressures, prehistoric humans evolved from hunter-gathers to farmers with well-established settlements. However, the Green Sahara did not last; the Earth's orbital precession slowly changed again, this time weakening and causing a slow southward contraction of the summer monsoon between 8,200 and 4,500 BP, with a relatively abrupt change ~5,000 BP (Wright, 2017). It is theorised that this contraction was aided by the pastoralists overgrazing and employing fire suppression, which changed the savanna to shrubland, reducing atmospheric moisture and decreasing soil fertility (Boissoneault, 2017). This change in climate was a major factor in the rapid collapse of the Old Kingdom in Egypt ~4,200 BP (Welc and Marks, 2014). A prosperous civilisation which existed for almost 500 years disintegrated in only a couple of decades because of extensive severe drought, catastrophic low floods of the Nile, continual crop failures and mass starvation.

Population growth

The increasing scarcity of freshwater is a critical issue for humanity, with the increasing global population being a significant driver (Ripple et al., 2017; Crist et al., 2022). At the same time, the per capita use of water is increasing as people move from rural to urban areas and from developing to developed countries, particularly as the global middle class grows (Steffen et al., 2015). The availability of freshwater at the local levels must be managed sustainably. Water is a limited resource: however, recycling wastewater and sewerage, desalination and removal of other pollutants requires further limited resources, including energy, which are expensive. Continuing population growth and climate change make the problem more difficult to deal with.

Difficulties in making predictions of future populations – global or urban – create considerable uncertainty in the predicted estimates. Many researchers have attempted to estimate the maximum human carrying capacity (or, more recently, the tipping point population) of the world for a sustainable future. The 65 estimates before 2012, using different models and assumptions, ranged widely from as low as 500 million up to the most common estimate of 8 billion, a number we have recently exceeded (Pengra, 2012). In 2017, the UN Population Division undertook a meta-study of past population estimates (UNDESA, 2017) and concluded that 'it is most likely that the global population will reach 9.8 billion in 2050 and 11.2 billion in 2100'. However, UN Reports in the past have not been reliable (Holm, 2000) and UN development targets not always achieved (Bradshaw et al., 2021), creating some uncertainty in the predicted populations (Pengra, 2012). O'Sullivan (2016) is particularly critical of the UN's population growth projections. Nonetheless, these diverse studies have produced some optimism that all is well (Economist, 2019; Hance, 2020). The question remains: can a good life be provided to all within regional water boundaries if they are better managed?

Considerable faith has been put in the demographic transition occurring to 'bend the population curve' as has already happened in many countries. However, it is not guaranteed to occur in all countries (see Pell, 2016 for a counter example; and Cleland, 2017 for the uncertainty of the sub-Saharan African demographic transition) and, even if it should occur, there is no guarantee that population growth will not restart at some future time, creating further uncertainty for urban planners. An unexpected situation that is currently occurring is due to many nations adopting de facto open national borders, allowing apparently organised mass migrations from the developing to the developed nations, so leading to an increase in unplanned urbanisation and chaos in many of the developed countries.

Conclusion

There are challenges in improving the global water cycle (Lall et al., 2008) and individual urban water cycles (Lezcano et al., 2021) by sustainable means, which are made more difficult with growing populations. As discussed above, urban water cycles are different in each city, depending upon local geography, demographics and weather patterns, which will change with global warming. Past civilisations on Earth collapsed because the leaders were not sufficiently knowledgeable or forward thinking (Diamond, 2011; Ialenti, 2020), which still appears to be a problem in many countries. Unfortunately, it is easier to see the collapse of civilisations in hindsight and being on the outside rather than on the inside (Power, 2000). Groundwater is a particular problem due to its invisibility to managers and ease of access by users. At the local level, there must be improvements in the use of water as outlined by the UN, including being better management and stricter regulation. Importantly, urban design must allow any underlying aquifers to be recharged to avoid infrastructure damage. It has been argued that there are uncertainties with attempting to estimate future populations, both globally and in urban settings, and with whether the demographic transition will necessarily occur and persist.

A solution to the increasing global population, which is driving global drying, amongst other environmental problems, is not impossible (Pengra, 2012; Perkins, 2017; Tucker, 2020). Particular attention must be paid to the effect of rising populations (including through migrations) on local water resources, especially groundwater, and the knock-on effect on urban sustainability. As aforementioned, water stress has frequently been linked with social tension and conflict, which should be avoided in any urban planning.

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