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Groundwater in Africa – is there sufficient water to support the intensification of agriculture from "Land Grabs"?

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Introduction

Large-Scale Land Acquisitions (LSLAs) or "land grabs" have over the last decade primarily focused on Africa. Of the top eleven countries that account for 70% of global LSLAs, seven (Sudan, Mozambique, Tanzania, Ethiopia, Madagascar, Zambia and Democratic Republic of Congo) are in Africa (Anseeuw et al., 2012). The total area of LSLAs in Africa is estimated to amount to 134 million hectares (Anseeuw et al., 2012). As the primary purpose of these LSLAs is agricultural including both food and non-food (e.g. biofuel) crops, a fundamental but unexplored hydrological assumption is whether the requisite water to sustain crop production exists. Indeed, this assumption underlies the accusation that "land grabs" are, in fact, "water grabs".

The question as to whether there exists sufficient water to sustain the intensification of agriculture in many parts of Africa is of importance to not only LSLAs but the proposed green revolution in Africa[1]. The latter is a central platform of the poverty alleviation strategies of many African countries. Robust answers to the water supply question remain elusive. Limited hydrometric networks in Africa – as in many parts of the globe – commonly restrict both direct analyses of available freshwater resources and the validation of estimates derived from remote sensing (e.g. Swenson and Wahr, 2009) or macro-scale modelling (e.g. Vörösmarty et al., 2005). An additional complication is that Africa is home to the planet's most variable rainfall and river discharge (McMahon et al., 2007) but national manmade capacities to store water (e.g. reservoirs) are among the lowest per capita in the world (Brown and Lall, 2006; Grey and Sadoff, 2007).

As the world's largest distributed store of freshwater, groundwater represents a potential source of water to enable the intensification of agriculture in Africa through irrigation. Indeed, dramatic increases in food production realised in South Asia and China since the 1970s have relied upon groundwater-fed irrigation. At present, only 5% of cultivated land in Africa is irrigated, well below the global average of 19.4% (Siebert et al., 2010). A key benefit of using groundwater in Africa is its slower response to changing meteorological conditions relative to surface water. As such, groundwater provides a natural buffer against climate variability (Calow et al., 1997; Calow et al., 2010). Furthermore, groundwater can be found in many environments so that sources can be sited close to the point of demand, minimising the requirement for extensive distribution networks (MacDonald and Calow, 2009). Groundwater is also commonly of suitable quality for agriculture though elevated concentrations of iron, fluoride or arsenic have been observed in some environments (Smedley, 1996; Edmunds and Smedley, 2005).. Indeed, across Africa, groundwater

[1] Alliance for a Green Revolution in Africa (http://www.agra-alliance.org/)

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has already proved to be vital in providing safe drinking water to improve health and reduce rural poverty (Carter and Bevan, 2008; Hunter et al., 2010).

Spatially explicit, quantitative information regarding available groundwater resources in Africa has, to date, remained extremely limited. In this paper, we discuss the availability of groundwater in Africa using results from new research and mapping (MacDonald et al., 2012). We also introduce some of the tools required to sustainably investigate and exploit the resource and the potential risks to groundwater and ecosystems from overuse and contamination of groundwater from intensive agriculture. A central question that these analyses seek to inform is where groundwater can sustain a green revolution in Africa without following the pathways of overexploitation and degradation that have occurred over much of Asia?

Maps of groundwater resources in Africa

Recent research has estimated the groundwater storage in African aquifers to be more than 0.5 million km^3, more than 100 times the annual renewable water commonly used in water scarcity assessments (MacDonald et al., 2012). Groundwater thus represents a freshwater resource that is of a fundamentally different scale to that available from rivers and lakes in Africa. Indeed, groundwater comprises more than 20 times average annual rainfall. Here we consider recently published quantitative maps of groundwater to discuss four aspects of the groundwater resources of relevance to irrigation: absolute groundwater storage, expected yields of individual wells and boreholes, depth to groundwater, and estimated average annual recharge to aquifers (Figure 1). At this continental scale, these maps can only give a rough guide of the variable groundwater conditions across Africa. Detailed investigations of local groundwater conditions would be essential before any investment in developing groundwater for irrigation.

Groundwater storage (MacDonald et al 2012). The largest groundwater reserves in Africa are found in large sedimentary aquifer systems in Libya, Algeria, Sudan, Egypt and Chad. Groundwater storage in these aquifers can be as high as 75×10^6 m^3/km^2 (equivalent to 75 m water depth) due to the high porosity and the thickness of the aquifers. Aquifers with the least storage tend to be weathered crystalline basement rocks where groundwater only occurs in the uppermost weathered mantle or in fractures; average groundwater volumes in basement rocks are estimated to be 0.5×10^6 m^3/km^2 (equivalent to 0.5 m depth). This small volume of storage is generally sufficient to buffer abstraction via community handpumps through dry years (MacDonald et al., 2009) but may be insufficient to sustain greater abstractions required for intensive irrigation.

Borehole yields (MacDonald et al., 2012). Groundwater is accessed and abstracted generally through drilling boreholes in which the permeability of the rocks constrains the rate at which groundwater can be abstracted. Figure 1 (b) shows a map of borehole yields that can reasonably be expected in different aquifers in Africa given appropriate technological expertise to locate and construct them. The maps show that remote from the high permeability sandstone aquifers, yields in excess of 20 l/s are difficult to find, and even yields of 5 l/s are not common. The map indicates the interquartile range of borehole yields so that higher yielding boreholes are possible to locate, particularly in river valleys, but may require more detailed site investigations. To put this in context, a large centre pivot irrigation system will require boreholes that can yield in excess of 50 l/s. Other intensive irrigation techniques generally demand well yields of more than 10 l/s to be efficient. However, a small community irrigation system will require much smaller yields, often less than 2 l/s.

Depth to groundwater (Bonsor and MacDonald 2011). Depth to groundwater is another important factor controlling accessibility and the cost of accessing groundwater (Figure 1c). At depths >100 m the cost of borehole drilling increases significantly due to the requirement for more sophisticated drilling equipment. Pumping costs also increase substantially with groundwater levels. The maps show that across much of central, western and eastern Africa, where the climate is wet or seasonally wet and basement geology predominates, natural groundwater levels are generally shallow, approximately 0 to 25 m bgl. Shallowest groundwater-levels (<7 m bgl) are estimated to be adjacent to perennial rivers. Deepest groundwater levels (>250 m bgl) are mapped in the major sedimentary basins in north Africa where average annual rainfall is low and aquifers are generally hundreds of metres thick. The large groundwater resources in north Africa are consequently expensive to develop.

Groundwater recharge (Döll and Fiedler 2008). Groundwater recharge is a measure of the renewability of groundwater resources (Figure 1c). Where groundwater recharge is low, high groundwater abstraction will deplete groundwater storage and the abstraction is ultimately unsustainable. For example, many of the large, north African aquifers are not actively recharged, but were recharged more than 5000 yr ago when the climate of the area was wetter (Scanlon et al., 2006; Edmunds., 2008). Abstraction from these aquifers is considered to be mining fossil groundwater. Away from the arid areas of Africa, groundwater recharge generally occurs on at least decadal timescales (Taylor et al., 2012), and ongoing monitoring can assist in identifying whether abstraction for irrigation is in excess of long term recharge and would deplete groundwater storage.

There is currently insufficient data to make meaningful regional assessments of water quality for Africa. However, individual studies have identified high concentrations of fluoride in the volcanic rocks of the East African rift valley (Edmunds and Smedley, 2005); and some areas with elevated arsenic concentrations (Smedley, 1996). Elevated natural concentrations of other parameters including iron, manganese and chloride can also be found in aquifers depending on local hydrogeological conditions. Contamination, particularly in urban areas can also be a problem (Taylor et al., 2009).

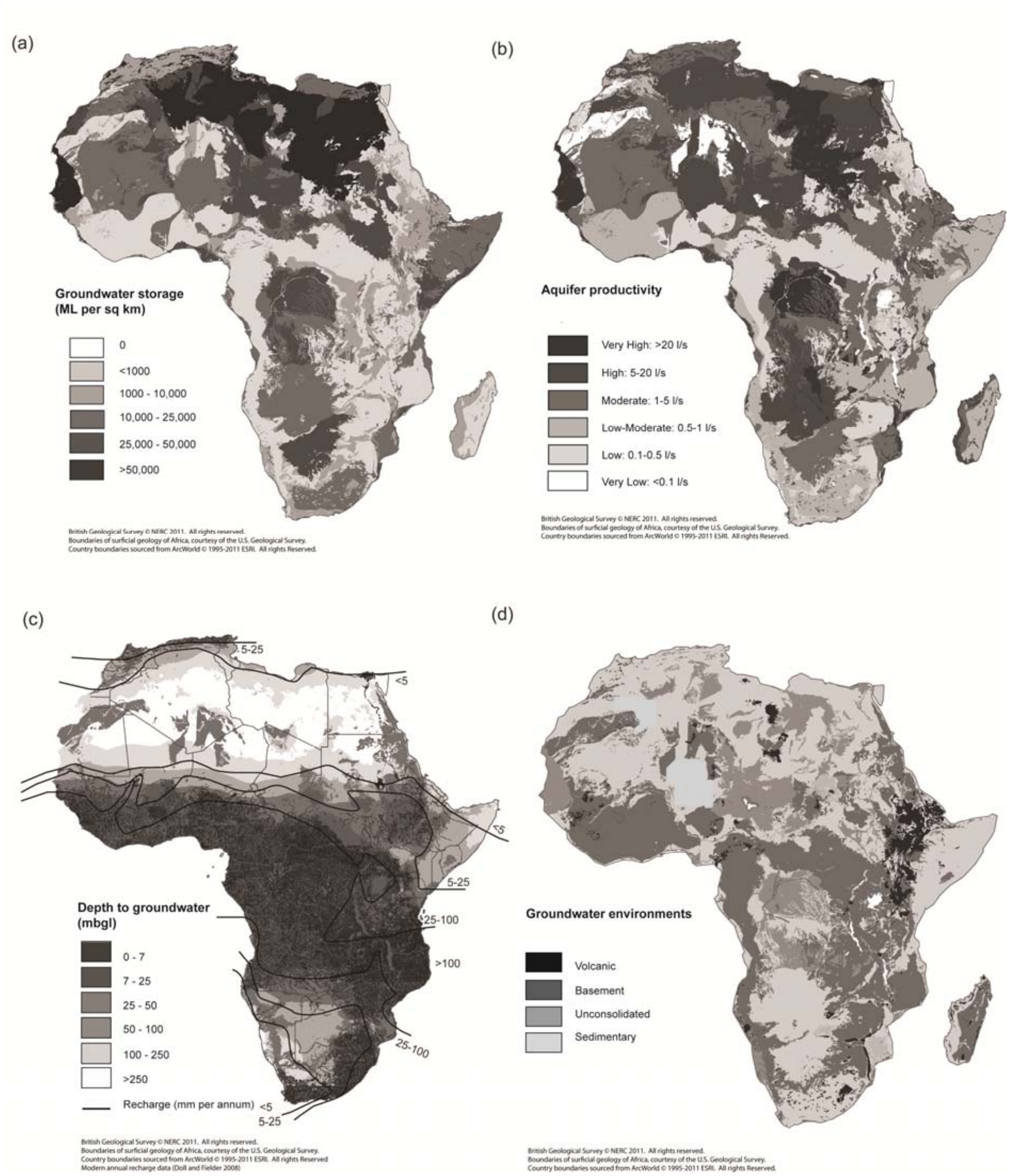

Figure 1 A series of groundwater maps for Africa: (a) Estimated groundwater storage Africa, based on the effective porosity and thickness of the aquifers (MacDonald et al., 2012); (b) the potential interquartile range of boreholes yields for appropriately sited and constructed boreholes. (MacDonald et al., 2012); (c) estimated depth to groundwater for Africa (Bonsor and MacDonald, 2011) and modelled groundwater recharge (Döll and Fiedler, 2008); and (d) hydrogeological environments (MacDonald et al., 2012).

Developing groundwater in Africa

The maps described above simplify the complexity and high variability in groundwater occurrence at catchment and local scales where groundwater will be exploited to sustain irrigation. Groundwater occurrence depends primarily on geology, geomorphology, and rainfall (both current and historic). The interplay of these three factors gives rise to complex hydrogeological environments with substantial variations in the quantity, quality, ease of access and renewability of groundwater resources. There are many different hydrogeological environments in Africa (Figure 1 d), but five of the most important are described below based on descriptions by MacDonald et al. (2005) and MacDonald and Calow (2009). Figure 2 shows schematic diagrams of groundwater occurrence in each environment.

Precambrian crystalline basement rocks occupy 34 % of the land surface of Africa and comprise crystalline rocks with very little primary permeability or porosity. Groundwater can be found within the weathered overburden or fractures in the bedrock. Yields of properly sited boreholes are commonly 0.1–1 l/s, but can occasionally be as high as 10 l/s. Geophysical techniques have been found helpful to locate boreholes in the most productive parts of the aquifers.

Consolidated sedimentary rocks occupy 37 % of land area of Africa, but mainly across un–inhabited areas. Sandstone basins can store considerable volumes of groundwater (Figure 1a) and support high yielding boreholes of 10–50 l/s. However, within low permeability mudstones and shales boreholes are often unsuccessful or only support yields of less than 0.5 l/s. Limestones rocks are soluble, and groundwater can flow through solution enhanced fractures. Borehole yields consequently can be very high (>20 l/s) but storage is more variable. Due to the variable and layered nature of sedimentary rocks a good understanding of the geology is required, often through trial drilling, geophysics and geological mapping.

Volcanic rocks occupy only 4 % of the land area of Africa and are found in east and southern Africa where they underlie some of the poorest and drought-stricken areas of Africa. Groundwater tends to be found in the fractures at the top and base of lava flows and within ash layers. Yields of 1–5 l/s and occasionally much higher can be achieved through well sited boreholes, but storage can be highly variable. Geophysics techniques, exploratory drilling and geological mapping have all been helpful in understanding and characterising groundwater resources in volcanic aquifers.

Unconsolidated sediments form some of the most productive aquifers in Africa. They cover approximately 25 % of the land surface. They have a high porosity and can store large volumes of groundwater; yields of 5–50 l/s are possible from individual boreholes. Unconsolidated sediments in river valleys are highly significant aquifers in Africa. They probably cover <1 % of the land area, but can be present within most river valleys. They can vary in thickness from several metres to 100 m thick, and have a high porosity. Individual yields of boreholes are commonly 1–10 l/s, and they can form important source for irrigation (Carter, 1997). In some places, where rainfall is low, unconsolidated aquifers can be dry, for example, the Kalahari Beds in southern Africa.

In every environment it is important to carry out pumping tests on successful boreholes to estimate their sustainable yield. Comprehensive water chemistry analyses should also be undertaken and where possible techniques used to estimate the long term average recharge of the groundwater. Where large well fields are planned, numerical groundwater models can prove useful in helping to test different pumping scenarios and design a sustainable abstraction regime. Drilling purpose built observation boreholes to monitor changes in the water-table as a result of pumping can be invaluable in determining whether pumping is sustainable or leading to degradation.

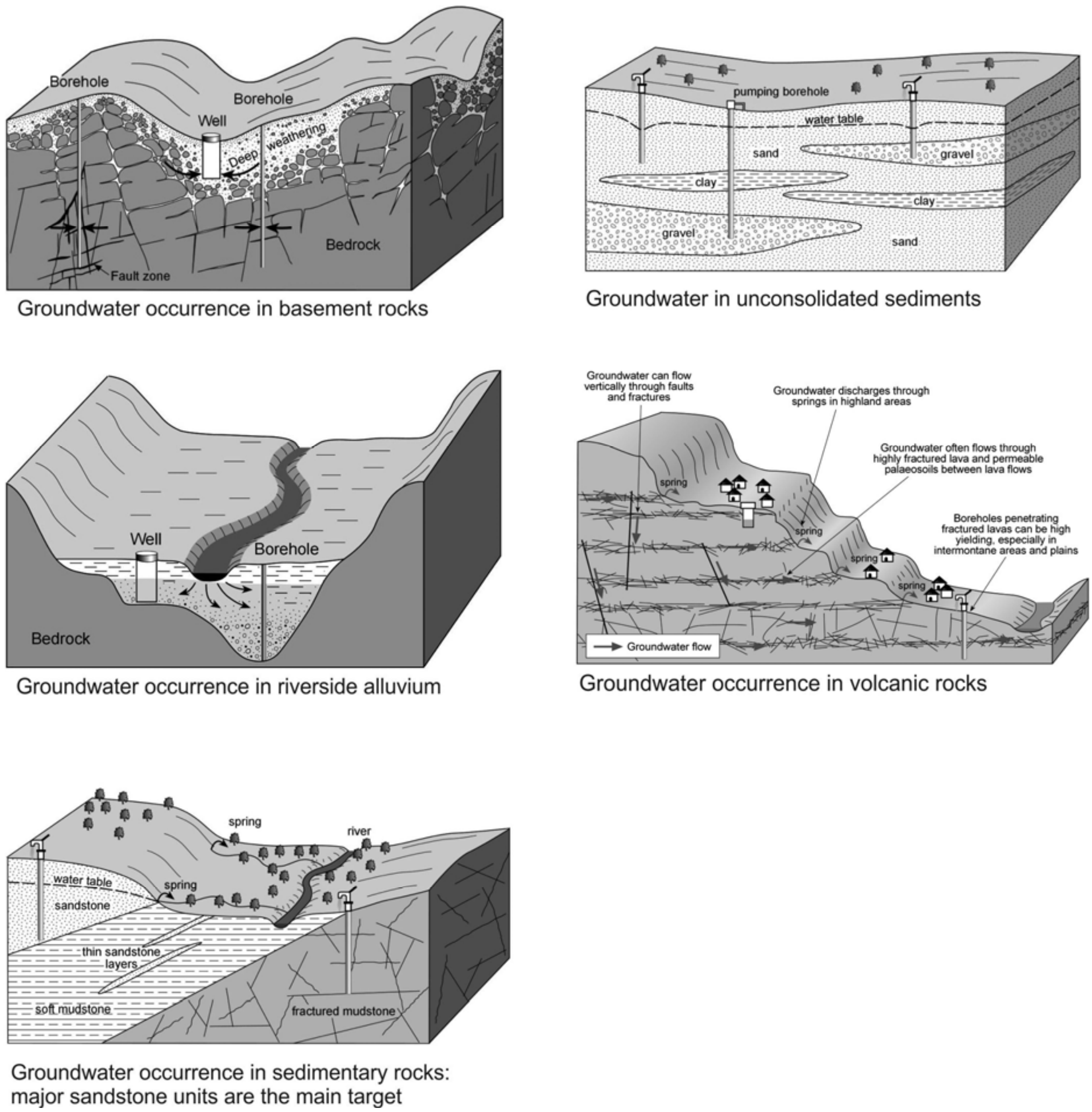

Figure 2 Groundwater occurrence in different hydrogeological environments in Africa (from MacDonald et al 2005 and MacDonald and Calow 2009)

Groundwater Degradation

Agriculture can severely degrade groundwater resources. The two main threats are over-exploitation and contamination. In most regions with an extended dry season, unconstrained groundwater demand by agriculture usually exceeds the availability of renewable groundwater through recharge (Garduno and Foster, 2010). This can lead to falling water levels within aquifers, increase pumping costs, groundwater salinization, and possibly land subsidence. The effects can take several decades to manifest themselves and not all are reversible. In some systems, even a small drop in groundwater levels can have devastating impacts on the flow of springs or the health of wetlands as the natural discharge of groundwater reduces to accommodate the abstraction (Tuinhof et al., 2011)

Fertilizer use and irrigation returns can degrade water quality by increasing nitrate concentrations and salinity (Scanlon et al., 2007; Ó Dochartaigh et al., 2010). Excess fertilizer and pesticides applied to crops can be leached into groundwater and persist for decades. Elevated nitrate concentrations in the water environment can have a major impact on ecosystems and can also have detrimental health effects for humans. This has led many countries to put in place tight controls on fertilizer application and a programme of regular monitoring of groundwater quality. The leaching of irrigation water back into groundwater can also increase the salinity of groundwater causing long term damage to the resource.

Some aquifers are more vulnerable to pollution than others. Also, aquifers can have different responses to high abstraction. Therefore, it is necessary to assess the risks posed by high abstraction and the use of fertilizers on a local scale in order to manage groundwater resources effectively. Almost all groundwater abstraction and land use activities will have some impact on groundwater, therefore, management strategies generally focus on minimising impacts, particularly for third parties, rather than eradicating them altogether.

Concluding Discussion

Groundwater is the largest freshwater resource in Africa and its exploitation will be essential to sustain growth in irrigated agriculture. Evident from the quantitative maps presented herein, groundwater is unevenly distributed and the potential for high yielding boreholes (> 20 l/s) to support intensive agriculture is limited. Smaller yields of approximately 1 l/s will be much easier to find. Given the diversity of hydrogeological environments and consequent uncertainty in groundwater occurrence, it is essential to characterise the local hydrogeological environment before presuming sufficient groundwater resources exist to sustain irrigation in any LSLA.

The presented continental-scale maps provide a first indication of the distribution of groundwater resources across the African continent. Worthy of note is that the smaller well yields available in low permeability aquifers such as Precambrian crystalline basement rocks occupying 34 % of the land surface of Africa may provide a solution to the intractable problem of sharing common-pool natural resources equitably (Hardin's "Tragedy of the Commons"). In low permeability aquifer environments, overpumping of an individual well is unable to exert much influence beyond the hectare-sized plot on which most farming is conducted in sub-Saharan Africa. As a result, the in situ hydrogeological conditions will restrict localised overexploitation naturally. The impact of aggregated groundwater use across a basin in these environments remains unclear and will nevertheless require careful monitoring.

Intensive agricultural activity can degrade groundwater resources. Abstraction that exceeds groundwater recharge can lead to declining water-tables and possible salinisation or even land subsidence. If fertilizers and pesticides are applied, groundwater is vulnerable to contamination as recharging water leaches these chemicals from the soil. Should groundwater be developed widely for irrigation in Africa, effective groundwater governance will become increasingly important to ensure that groundwater is available for other uses (drinking water) and future generations.

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