The Paradoxical Hydrology Of Tonlé Sap Lake: Groundwater Extraction And Land Subsidence

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Abstract

A close examination of Tonlé Sap Lake reveals a paradox — its flood extent has increased despite a reduction in water volume. Agricultural intensification in Cambodia has led to unsustainable rates of groundwater use for irrigation. This paper postulates that land subsidence due to an over extraction of groundwater is the main reason for the lake's paradoxical hydrology. Land subsidence has altered Tonlé Sap's morphology (i.e. the lake has become shallower), thereby leading to an expansion in its areal extent. The hydrological complexities of the Tonlé Sap gesture towards the tension between the country's need for economic sustainability (from cultivating rice) and that of environmental sustainability (sustainable use of groundwater resources).

Introduction

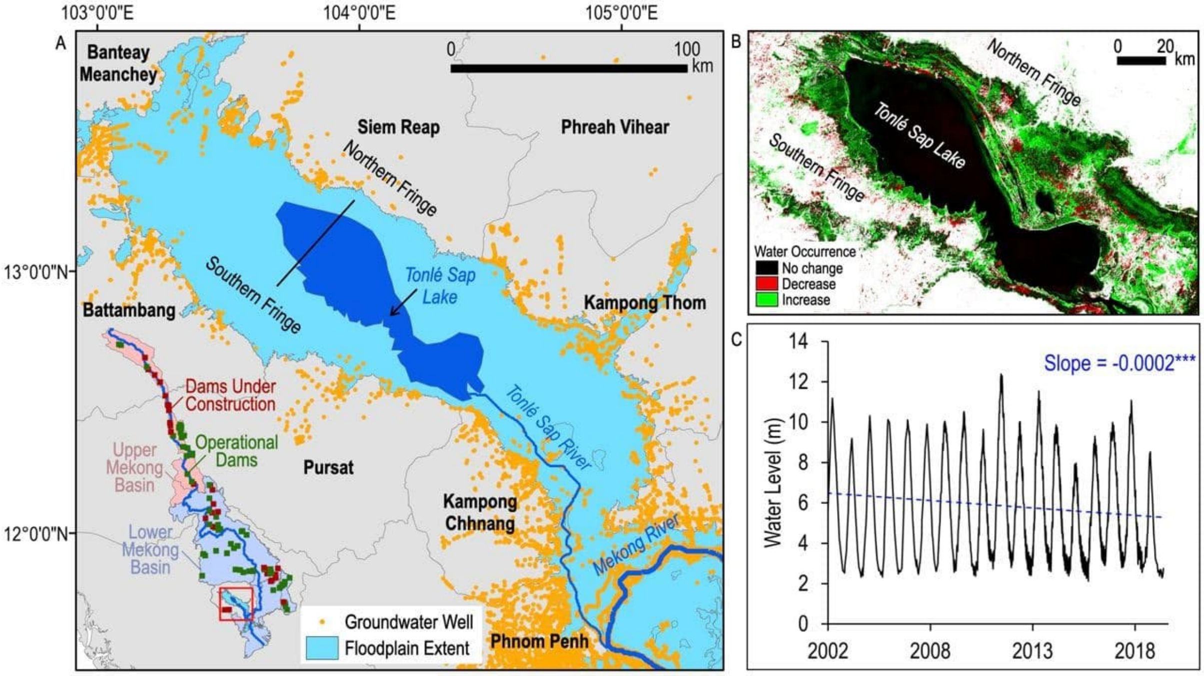
The Tonlé Sap Lake is located at the lower Mekong Basin, and is connected to the Mekong river via the Tonlé Sap river in Phnom Penh, Cambodia (Figure.1A). During the dry season, (December to February), the water level of Mekong river falls, and Tonlé Sap Lake provides 50% of its total inflow to the Mekong delta (Fuji et al., 2003; Chadwick et al., 2011). There are four main sources of inflow into Tonlé Sap Lake: majority of the inflow stems from the Mekong river (57%), followed by 30% inflow from Tonlé Sap neighbouring tributaries and 13% inflow contribution from precipitation (WUP-FIN, 2006). The surface area of the lake fluctuates from an average of 2,600 km2 to a peak of 15,000 km2 during the wet season (Arias et al., 2012).

This largest freshwater lake in Southeast Asia and its annual flood pulse supports a rich biodiversity (Lohani et al., 2020) and in turn, the aquaculture industry. Such an industry provides the Cambodian population with 80% of its protein consumption (Baran et al., 2006; Kummu et al., 2005; Kummu et al., 2014). Approximately two-thirds of Cambodia's fish supply comes from Tonlé Sap basin, which contributes to 10 to 12% of Cambodia's gross domestic product (GDP) (Chadwick et al., 2008), Tonlé Sap's ecological value is recognised internationally, and it has been designated as a Biosphere Reserve of UNESCO (Campbell et al., 2006).

Recent studies have shown that Tonlé Sap's inundated volume has been shrinking over the years (Ji et al., 2018; Wang et al., 2020). Multi-mission satellite altimetry from the Database for Hydrological Time Series of Inland Waters (DAHITI) has revealed that Tonlé Sap's water level has been declining over time (from 2002 to

2020; Schwatke et al., 2020). Global warming and the construction of numerous hydropower dams have been identified as the main causal factors for such a dwindling water volume (Piman et al., 2013; Wang et al., 2020). Since the Mekong River is directly connected to Tonlé Sap, a reduction in the river's discharge is likely to contribute to a reduction in the lake's inundated volume.

Figure 1. A: Map of study area and locations of groundwater wells; Inset map consists of the Lower and Upper Mekong Basin and location of operational dams and dams under construction. **B:** Map of surface water occurrence showing an increase in surface water occurrence at the northern and southern fringe of Tonlé Sap Lake (data from Pekel et al., 2016). **C:** Water level-time series graph showing a decreasing water level in Tonlé Sap Lake (Schwatke et al., 2020).



Nonetheless, a rather unusual phenomenon pertaining to the Tonlé Sap has been observed. The water occurrence change intensity around the lake has indicated an increase in the lake's flood extent from 1984 to 2019 (Pekel et al., 2016) around its southern and northern fringes, in spite of a shrinking lake volume. This paper seeks to investigate the causes of such a paradoxical phenomenon while hypothesising that land subsidence from excessive groundwater use is the main reason for the expansion of Tonlé Sap's flood extent. Although researchers have studied how the water volume in Tonlé Sap (Frappart et al., 2018) and its inundated area (Ji et al., 2018; Wang et al., 2020) have varied separately over time, the causal links between the two (i.e. volume and inundated area) have not been addressed. Moreover, land subsidence in Angkor Wat, Siem Reap has been reported (Chen et al., 2017; Chen et al., 2019), there has been a paucity of data on possible land subsidence and related morphological changes around Tonlé Sap.

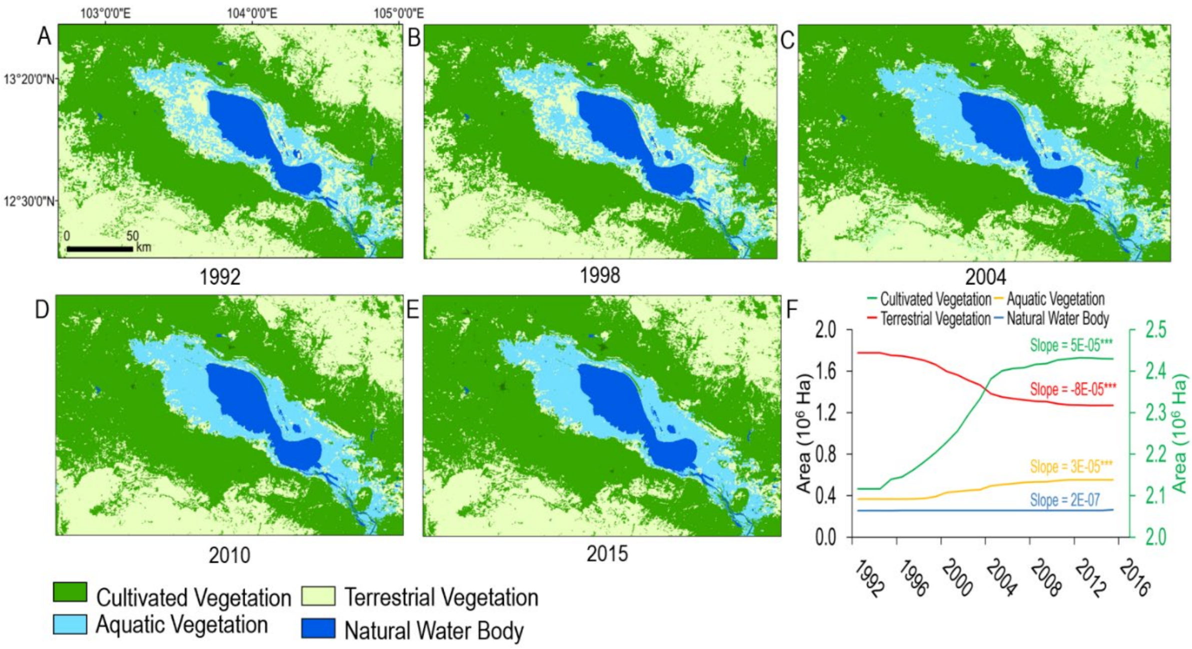
This paper details the severe ramifications of unsustainable forms of agricultural intensification that draw excessively on finite groundwater (re)sources. The hope is for policy makers, urban/rural planners to better calibrate the scale and rate of economic production as well as managing water resource use more carefully. The discussions on the paradoxical hydrology of Tonlé Sap can also inform lake science in the Anthropocene more broadly.

Data and Methods

Land Cover Change mapping was done to measure the conversion of naturally vegetated areas into crop-lands from 1992 to 2015. These maps at 300m spatial resolution (WGS83 geodetic datum) were retrieved from the European Space Agency (ESA) Climate Change Initiative-Land Cover project, with the classes defined by the UN Land Cover Classification System (ESA, n.d.). 24 annual land cover maps were aggregated into three major land cover classes: natural and semi-natural terrestrial vegetation, cultivated vegetation and aquatic vegetation (e.g. permanently flooded land). These datasets were used to detail the spatio-temporal extent of land cover changes for the northern and southern fringes around Tonlé Sap Lake.

A broad comparison of the 24 floodplain-wide land cover maps from 1992 to 2015 revealed expected changes in the spatial extent of terrestrial, cultivated and aquatic vegetation. During the 24-year period, the terrestrial vegetation cover around Tonlé Sap region revealed a statistically significant decreasing trend (likely due to deforestation and agricultural expansion, Figure. 2A-F; Lohani et al., 2020). In contrast to terrestrial vegetation, the cultivated vegetation generally displayed a statistically significant increasing trend from 1992 to 2015.

Figure 2. A-E: Series of land cover maps (A-E) showing an increase in the area of cultivated vegetation and aquatic vegetation and a decrease in area of terrestrial vegetation from the period of 1992 to 2015. F: Time-series graph showing the quantitative increase and decrease of the different land cover classes over time.



Data on the groundwater level in Siem Reap, a province at the northern fringe of Tonlé Sap Lake was represented as vis-a-vis water level versus time graphs to show a decline in the water table over a 5-year period from 2003 to 2007 (Figure 2F). Primary data from Sok and Choup (2017) research was also mobilised to analyse the spatiality of groundwater use in Cambodia.

Agricultural expansion and intensification

80% of the population in Cambodia live in rural areas and are engaged in agricultural activities for a living. In particular, 65% of its population cultivates rice, which contributes to 27% of the country's gross domestic product (Cramb, 2020; Mahood et al., 2020). Cambodia's economy is primarily dependant on its agricultural sector, which accounts for 27% of its National Gross Domestic product, and 65% of its labour force (Smith and Hornsbuckle, 2013). Rice production is a fundamental aspect of food security and economic livelihood in Cambodia (Smith and Hornsbuckle, 2013; Wokker et al., 2013). At least 2000 varieties of rice are being grown around different parts of the Tonlé Sap (Arias et al., 2013). Different varieties of rice are cultivated during the wet and dry seasons in Cambodia (Vernooy, 2015). Dry-season rice is mainly cultivated at lowland areas where surface irrigation is available for seasonal flooding. Wet-season rice is mainly cultivated around lowland areas, upland margins and deep-water areas (Vernooy, 2015).

Apart from rapid population growth and a corollary increase in demand for food, agricultural intensification is largely driven by political-economic motivations. In 2004, the Cambodian government implemented a National Export strategy in light of trade liberalisation and promoted rice as "white gold" that would bring about economic development (Cramb et al., 2020; Mahood et al., 2020). Rice production was boosted in order to attain the goal of exporting "one million metric tonnes of rice" in five years (Cramb et al., 2020; Royal Government of Cambodia, 2010; Thomas et al., 2013), Accordingly, Figure 3 illustrates a dramatic increase in paddy production from 1961 to 2014. Likewise, Figure 4 shows that the production of most crops (including rice) has increased tremendously over time, alongside rubber and cassava.

Agricultural intensification typically entails a double cropping of rice during the wet and dry seasons (made possible by irrigation systems). Such an exponential growth in rice production is brought about by an expansion of cultivated land (Cramb et al 2020) and the installation of more infrastructure for irrigation (Smith and Hornbuckle, 2013). Cultivated agricultural areas account for 3.7 million hectares of land in Cambodia, (with 76% of it dedicated to paddy crops and 26% of it to non-rice crops (Ket, 2019; MWRM, 2003).

Rice cultivation has been the backbone of Cambodia's agricultural sector for decades; but local farmers have been more open to crop diversification (e.g. growing maize, cassava, peanut and soybean) in the recent years so as to boost their income (Newman et al., 2014). Farmers who engage in crop diversification cultivate non-rice crops during the dry season and rice during the wet season (Robins, 2014). The intention to grow non-rice crops has contributed to the clearing of forested upland areas, where only 2% of the area is used for rice cultivation.

Figure 3: Area of rice field, paddy yield and production in Cambodia (source: www.ricepedia.org)

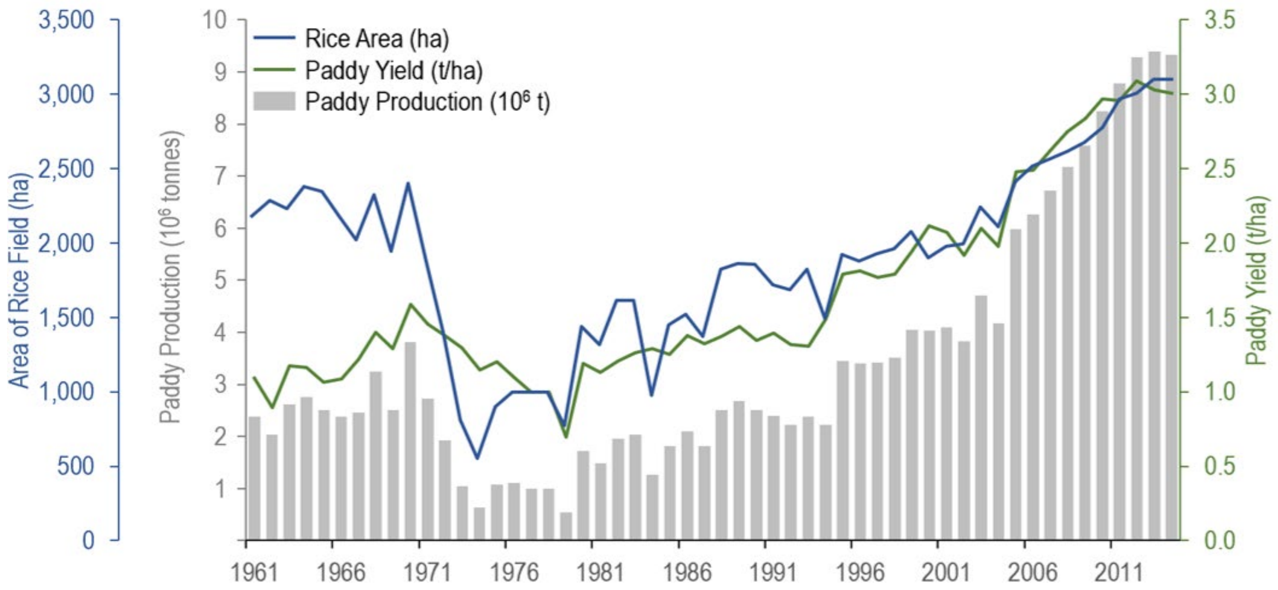
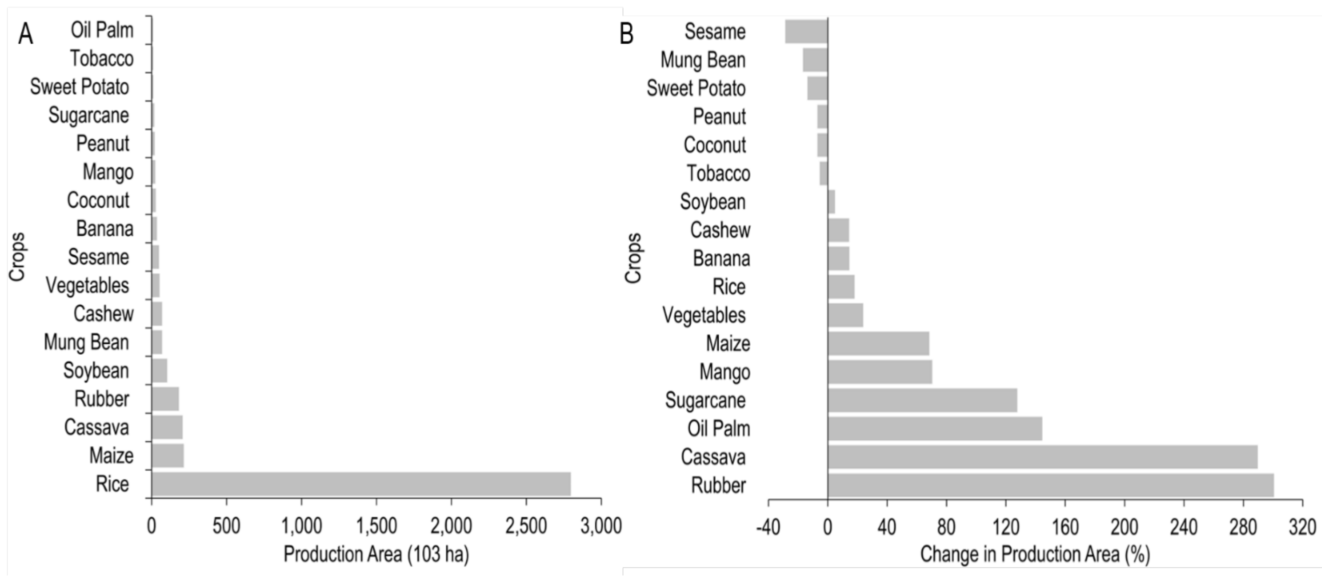


Figure 4 Crop production area and change in crop production in Cambodia (Vernooy, 2015)



Groundwater extraction

Agricultural intensification has engendered an increase in groundwater extraction for irrigation, especially in the south-eastern lowlands of the basin (Figure 5; Johnston, et al., 2013; Erban et al., 2016; Sok and Choup, 2017). Most of Cambodia's agricultural land is underlain by alluvial deposits. These deposits operate as excellent shallow aquifers (five to ten metres below the ground surface) and groundwater (as opposed to surface water) has been construed as a convenient source for irrigation. Such aquifers are also perceived to have quick recharge rates and extraction is made possible with sink tube wells and readily available small portal pumps (Bell et al., 2005).

It has been argued that more than 80% of the total groundwater use in Cambodia is exploited for agricultural activities (Sok and Choup, 2017) and is increasing rapidly. Figure 5 and 6 depict the normalised percentages of groundwater use across Cambodia's 24 provinces while Figure. 7 shows a reduction in the country's groundwater level over a period of five years (2003 to 2008). Groundwater extraction could lower the water table and aquifer depletion implies that wells will eventually dry up (Ngoc et al., 2015; Vote et al., 2014). This is especially the case since the number of tube wells (in Prey Veng for example) has multiplied (from 1,600 to 25,000 in over a decade; IDE, 2005; Johnston et al., 2013; Sok and Choup, 2017; Cramb et al., 2020; Smith and Hornsbuckle, 2013).

Regardless, statistics on groundwater use in Cambodia remains scarce and unreliable (Ngoc et al., 2015). Besides the existence of undeclared private or illegal wells across the country, mechanised pumps for groundwater extraction are installed at an approximate rate of 20% per year (IDE, 2005), possibly more quickly than they can be mapped. Unsurprisingly then, groundwater use is immensely difficult to monitor and regulate.

Figure 5 Percentage of groundwater use in Cambodia (Sok and Choup, 2017)

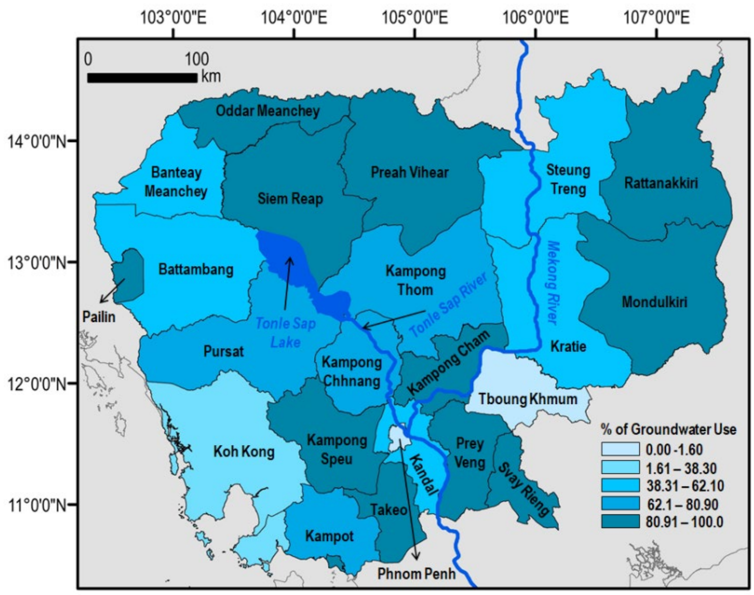


Figure 6 Normalised values of groundwater usage by the 24 provinces in Cambodia (Sok and Choup, 2017)

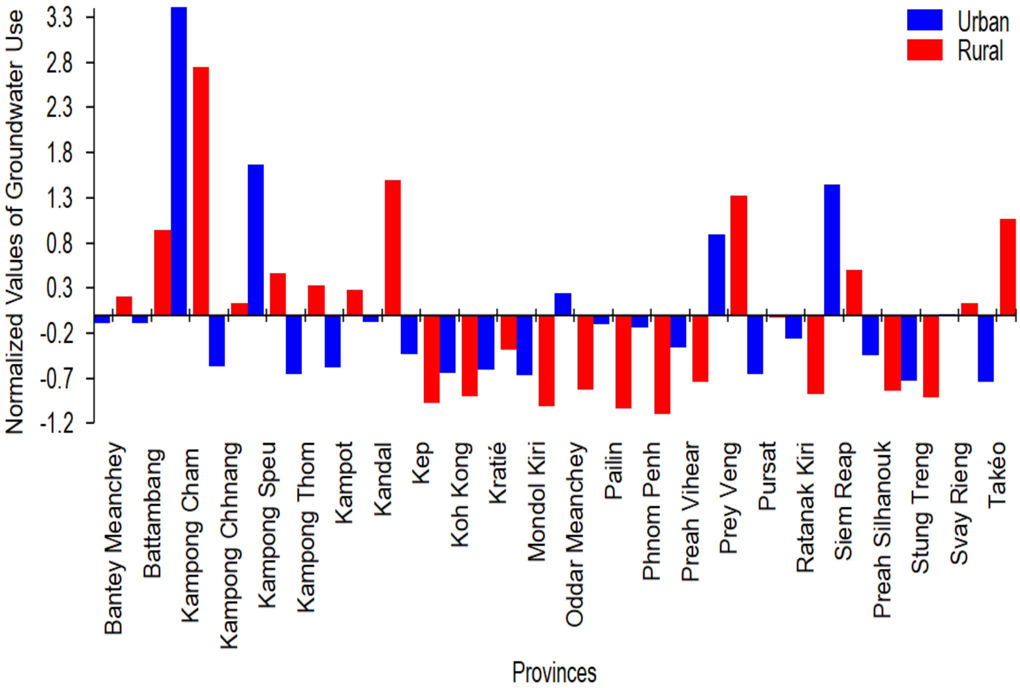
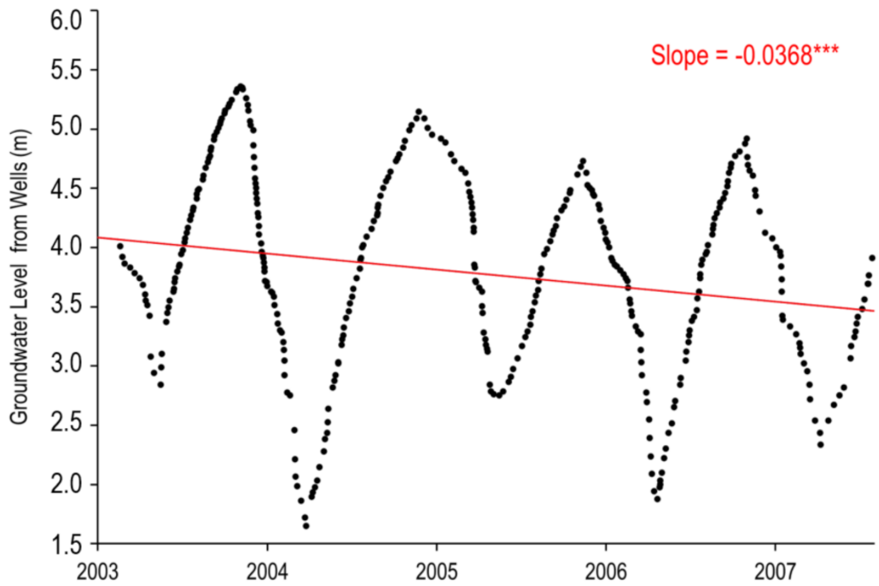
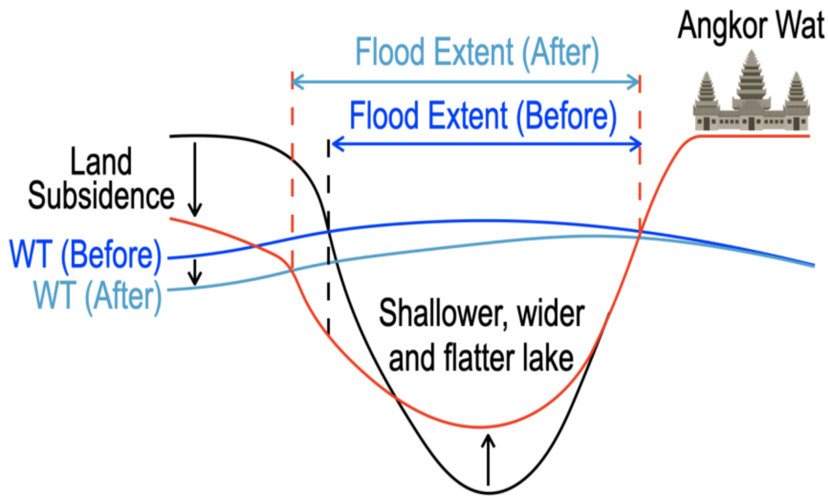


Figure 7 Decreasing groundwater level from the surface in Siem Reap.



Groundwater extraction has been identified as a key factor of land subsidence Tonlé Sap (Sok, 2017; Erban et al., 2014; Higgins et al., 2014; Minderhoud et al., 2018), especially when the rate of groundwater extraction exceeds that of recharge (Johnston et al., 2013). With reference to Figure 8, the probable lowering of the ground surface impinges on the lake's morphology, such that more of its surrounding areas are flooded. This arguably accounts for Tonlé Sap's paradoxical hydrology.

Figure 8. The schematic diagram illustrates the causal relationship between the lowering water table and land subsidence due to groundwater extraction, resulting in an increase in flood extent.



Concluding thoughts

This paper has highlighted the perils of unsustainable rates of agricultural intensification and groundwater extraction for irrigation in Cambodia. Some of these 'perils' pertain to land subsidence around Tonlé Sap Lake and an expansion of its flood extent. While the 'perils' of over-extracting surface water and groundwater are more obvious (e.g. aquifer depletion, and increase in water stress), the 'perils' or implications of Tonlé Sap's paradoxical hydrology remains largely unknown, particularly with respect to its flooding extent. More research is thus required in this aspect, including viable and sustainable management strategies for monitoring and optimising the use of water for irrigation (e.g. irrigation technologies that reduce evaporative loss).

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