Journal of Hydrology 535 (2016) 85–92

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Closing the irrigation deficit in Cambodia: Implications for transboundary impacts on groundwater and Mekong River flow

Laura E. Erban *, Steven M. Gorelick

Department of Earth System Science, Stanford University, 473 Via Ortega, Stanford, CA 94305, United States

ARTICLE INFO

Article history:
Received 18 October 2015
Received in revised form 21 December 2015
Accepted 26 January 2016
Available online 3 February 2016
This manuscript was handled by Geoff Syme, Editor-in-Chief, with the assistance of Craig T. Simmons, Associate Editor

Keywords:
Paddy
Agricultural water use
Dry season rice
Groundwater pumping

SUMMARY

Rice production in Cambodia, essential to food security and exports, is largely limited to the wet season. The vast majority (96%) of land planted with rice during the wet season remains fallow during the dry season. This is in large part due to lack of irrigation capacity, increases in which would entail significant consequences for Cambodia and Vietnam, located downstream on the Mekong River. Here we quantify the extent of the dry season "deficit" area in the Cambodian Mekong River catchment, using a recent agricultural survey and our analysis of MODIS satellite data. Irrigation of this land for rice production would require a volume of water up to 31% of dry season Mekong River flow to Vietnam. However, the two countries share an aquifer system in the Mekong Delta, where irrigation demand is increasingly met by groundwater. We estimate expansion rates of groundwater-irrigated land to be >10% per year in the Cambodian Delta using LANDSAT satellite data and simulate the effects of future expansion on groundwater levels over a 25-year period. If groundwater irrigation continues to expand at current rates, the water table will drop below the lift limit of suction pump wells, used for domestic supply by >1.5 million people, throughout much of the area within 15 years. Extensive groundwater irrigation jeopardizes access for shallow domestic water supply wells, raises the costs of pumping for all groundwater users, and may exacerbate arsenic contamination and land subsidence that are already widespread hazards in the region.

Published by Elsevier B.V.

1. Introduction

Cambodia and Vietnam, which share the Mekong River Delta, rely on rice production exports for their economic well-being. Vietnam is the world's third largest exporter of rice, however, exporting over six times as much as Cambodia (FAO, 2015). The discrepancy arises in part because the irrigation capacity of Cambodia lags far behind its neighbor. Vietnam irrigates ~60% of paddy grown in the Delta, with year-round cropping in this region contributing roughly half of national production (MRC, 2010). Cambodia, on the other hand, irrigates just ~10% of its rice crop (MRC, 2010), most of which is grown during the wet season of the monsoon (May to November). Though dry season irrigation capacity is certainly not the only factor limiting Cambodian rice production, it is a fundamental one undergoing rapid change.

Irrigation with groundwater is on the rise in Cambodia and may outpace increases in access to surface water sources. Planned surface water infrastructure initiatives and upgrades are expected to increase the planted area of the dry season crop by 45% over the next 20 years (MRC, 2009). Meanwhile, installation of motorized-pump irrigation wells has already increased at a rate of ~20% *per year* over the period 1996–2005 (IDE, 2005). Our satellite-based analysis of land-cover change indicates that the area irrigated with groundwater is growing at a similarly high rate. This unplanned growth may lead to adverse effects that include water table decline, making groundwater more difficult to access and costlier to lift, land subsidence, and potential exacerbation of naturally-occurring arsenic contamination (Winkel et al., 2011; Erban et al., 2013). The proliferation of mechanized groundwater irrigation pumps has already lead to extreme aquifer depletion elsewhere in the broader region (e.g., northern India, northeast China), with unfavorable outcomes (see, e.g., Shah, 2007) that may yet be avoided in Cambodia.

Here we evaluate the major hydrologic consequences of closing the Cambodian "irrigation deficit" (deficit), defined as the water needed for irrigation of dry season (December–April) rice, quantifying two outcomes. The first outcome is reduction, via surface water diversions, of Mekong River flow to Vietnam. Reductions in flows threaten Vietnam's current irrigation system by lowering

* Corresponding author at: US EPA, ORD, NHEERL, Atlantic Ecology Division, 27 Tarzwell Drive, Narragansett, RI 02882, United States.

E-mail addresses: lerban@stanford.edu (L.E. Erban), gorelick@stanford.edu (S.M. Gorelick).

http://dx.doi.org/10.1016/j.jhydrol.2016.01.072
0022-1694/Published by Elsevier B.V.

water levels in the country's extensive canal network. The second outcome, aquifer depletion due to groundwater pumping, poses a threat to the viability of pervasive low-cost suction pumps and raises the cost of extraction for groundwater users in Cambodia and adjacent areas of Vietnam. We discuss these outcomes and related potential hazards associated with over-exploitation and expansion of groundwater for irrigation over the next 25 years as southeast Cambodia strives to develop its agricultural base.

2. Methods

2.1. Irrigated area

We use two sources of data for determining the dry season deficit area (i.e., land area only planted with rice during the wet season) in the Cambodian catchment of the Mekong River. First, a recent agricultural survey (2009, in CLEAR, 2012) provides commune-level (mean size: 110 km^2) statistics. Variables describing rice cultivation practices include the total planted area of wet and dry season crops, and classification by water supply type: rainfed, post-flood temporary ponding (i.e., "recession"), or irrigation. Second, we perform an analysis of satellite remote sensing data, validated by our ground observations. The remote sensing analysis is needed for two reasons: (1) the survey appears to underreport dry season rice production, and (2) it does not provide multiple time points with which to determine rates of change of dry season rice cultivation. Dry season deficit areas determined by each method are shown in Fig. 1.

The remote sensing analysis was conducted in Google Earth Engine (GEE), a cloud-based platform for conducting on-the-fly manipulations of publicly-held satellite data collections and products. GEE facilitates the rapid analysis of large amounts of spatio-temporal and intercomparison across sensor platforms. We used the Normalized Difference Vegetation Index (NDVI) data products from two sensors, MODIS and LANDSAT-5. The former has high temporal (daily) and coarse spatial (up to 250 m) resolution, and is better suited for compiling mosaics at the national scale. The nominal repeat period of LANDSAT-5 is 16 days, however data are available much less frequently in Cambodia, and many of these have high cloud cover. The higher spatial resolution of LANDSAT (30 m) is needed to discern field-scale (∼100 m) changes in vegetation cover.

We used the MODIS NDVI 16-day composite archive (products MOD13Q1 and MYD13Q1) in GEE to calculate the dry season deficit area at the national scale. Composites are processed to be largely cloud-free. For each year available (2003–2015), we selected imagery dates during the months of January–March for the dry season and August–October for the wet season (6 composites in each season). For each dry or wet season, we calculate the maximum pixel-wise NDVI. The procedure circumvents issues with remaining cloud-cover in the composites and variability in planting dates, indicating vegetation presence at any point during the 3-month period. We used an NDVI threshold of 0.55, which minimizes the deviation between survey and satellite-based estimates in 2009 (when both are available) and agrees with results from a rice cropping intensity study based on MODIS data and conducted in the Vietnamese Mekong Delta (Chen et al., 2011), was used to distinguish vegetated pixels. We applied a binary mask to wet season pixels above the threshold and dry season pixels below it. Multiplication of the two masks yields the area that was vegetated during the wet season but not during the dry season of a given year. The average of these annual values from both products is our estimate of the countrywide dry season deficit area.

In southeastern Cambodia, where the only known time-series records of groundwater levels are available, we estimate the change in dry season groundwater-irrigated area using the LANDSAT record. Due to the more limited availability of the LANDSAT data, we consider a base period from 1995 to 2004 and a comparison period from 2007 to 2011 during which we estimate rates of change. We select images from the same 3-month dry season specified above, and pixels with maximum NDVI values >0.4 (appropriate values vary among sensors). We assume that the maximum extent of natural vegetation, which is subject to interannual variability, is captured during the base period, and that additional high-NDVI areas seen in the comparison period are irrigated fields. To exclude fields irrigated with surface water, we apply a 100 m buffer to all mapped canals, rivers and permanent lakes. Ground-control points throughout the domain visited in February, 2010 confirm the presence of groundwater-irrigated rice fields at eight

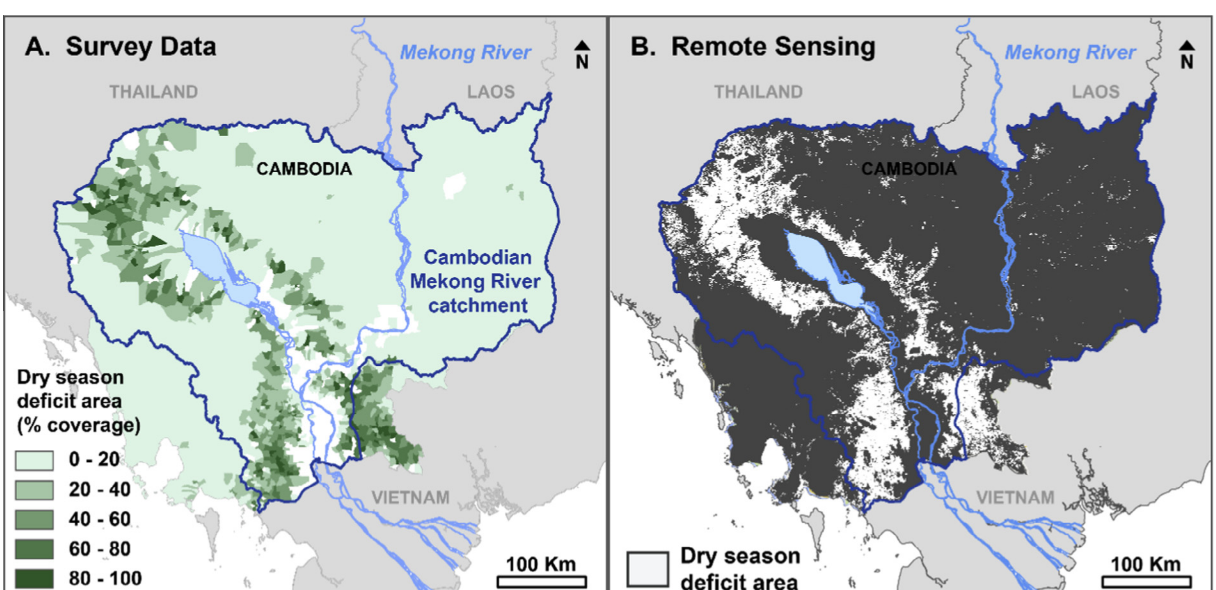

Fig. 1. Seasonal rice production in Cambodia (2009). A. Surveyed areas where the rice-planted area is greater in the wet than dry season. Difference expressed as percent of commune area. B. Remotely sensed (MODIS NDVI) dry season deficit area. The dark blue line delineates the area of Cambodia found within the Mekong River catchment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)