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

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Abstract

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.

Keywords paddy, agricultural water use, dry season rice, groundwater pumping

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 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 km²) 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 Figure 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 250m) 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 (30m) is needed to discern field-scale (~100m) 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 1995-2004 and a comparison period from 2007-2011 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 100m 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 locations (two of which are shown in Fig 2B), and groundwater-irrigated melons at one location, which does not exceed our NDVI threshold (the melon-planted area was more sparsely vegetated). The annual rate of change (assuming geometric growth) in groundwater-irrigated area, aggregated by commune, is calculated from the difference observed over the 7 years (2004-2011) elapsed between the base and comparison periods.

2.2 Irrigation Water Requirement: The total dry season irrigation requirement is estimated from field studies of dry season rice grown in the Cambodian lowlands (Phengphaengsy and Okudaira, 2008, Someth et al., 2009) and conditions in southeast Cambodia where our quantitative analyses were conducted. In the field studies, crop evapotranspiration (ET_c) averaged 493 mm (358 mm – 628 mm). During the months when dry season rice is grown in

southeast Cambodia, rainfall averages 145 mm (116 mm – 173 mm). Infiltration was estimated using a reasonable range of values for hydraulic conductivity of the surficial clay soil (0.0018 - 0.0022 m/d), a unity gradient for shallow ponded water in the paddy, and the crop growing period (110 d), to average 218 mm (197 - 239 mm), or ~2 mm/d. As such, the irrigation requirement ($ET_c + \text{Infiltration} - \text{Rainfall}$) for a dry season crop grown in our study area is ~567 mm (382 mm – 751 mm).

We allocate the total irrigation water requirement on a monthly basis throughout the growing season according to crop phenology and the range of typical planting dates, using FAO's CROPWAT (v8). Climate data is derived from CLIMWAT using the Phnom Penh station. High-yield rice varieties of short duration (105-115 days) make up 70-80% of dry season rice grown in Cambodia (FAO, 2002), with planting dates ranging from the beginning of November to January and harvests as late as April. To account for different planting times and soil conditions, we: 1) perturb (by doubling and halving) the default CROPWAT input parameters for a rice crop grown on clay soil and, 2) adjust the start date of a 110-day crop from 1-Nov to 1-Jan. Crop coefficients range from 0.3 – 1.2 over the growing season, depending on crop growth stage (seven stages from nursery to late season maturity) and related soil flooding status.

The CROPWAT-based timing of the irrigation water requirement is used as the basis for groundwater pumping in our model. Since groundwater is pumped directly onto adjacent fields, we do not include an additional water requirement to compensate for conveyance losses. Nor do we include other losses due to misapplication of irrigation water by farmers. We therefore consider our estimates of pumping for irrigation to be conservative (could be higher if groundwater resources were wasted).

2.3 Groundwater Depletion: To analyze the major hydrologic impacts of rapidly increasing groundwater use for irrigation, we developed a predictive model of the aquifer system in southeast Cambodia (see Fig. 2A). In this region, which includes most of the Cambodian Mekong Delta, groundwater levels, (i.e., hydraulic heads) were monitored monthly in a distributed network of 49 wells over the period 1996-2008 under an EU-funded PRASAC program. These hydraulic head data allow for comparison to transient groundwater model results. We know of no other area of the country where such long-term records exist. Therefore we develop a model that predicts impacts of groundwater development in southeast Cambodia only. This region contains: 1) one of the country's most productive alluvial and only transnational aquifer system, and 2) over 10% of rice-cultivated land in Cambodia. Also noteworthy, wells in the provinces in this region (4 provinces included) have arsenic in excess of the Cambodian standard of 50 µg/L at occurrence rates between 4.4% and 41.3% (RDIC, 2012).

Our groundwater flow model (in MODFLOW) includes a surficial clay aquitard overlying a single shallow, sandy initially confined aquifer. Conversion to water-table (unconfined) conditions in this shallow aquifer occurs during the pumping period, subject to spatially variable clay thickness and pumping rates. Although deeper aquifers likely exist, as continuations of known units on the Vietnamese side of the Delta (see Erban et al., 2013, Erban et al., 2014), they are not exploited in this part of Cambodia. The thicknesses of the two modeled units (aquitard mean: 20m, aquifer mean: 79m) were determined from stratigraphic logs recorded for wells in the monitoring network. Since these logs typically do not extend to the bottom of the aquifer, we assume it has a maximum depth of 100m below zero datum of MSL, corresponding with the deepest logs and exceeding the depth of most, possibly all, wells in this part of Cambodia. Layers were modeled as convertible confined - unconfined (i.e., transition

between conditions is allowed). The horizontal model discretization is 1km x 1km, and it contains 39,910 active cells (19,955 in each layer). The temporal discretization is daily.

Hydraulic properties were based on our previous detailed modeling effort in the Delta (Erban et al., 2013) and match of simulated values to data through the procedure described below. Results are consistent with those derived from pumping tests and established values for sediment types from field studies and the literature. Values of hydraulic conductivity were homogenous in each model layer, except for a small lower-K region of the aquifer adjacent to the northeastern highlands. Specific storage (for confined conditions) and specific yield (for unconfined conditions) values were homogenous within each layer. Specific storage is greater for clays (more compressible) than for sands, while specific yield is greater for sands (more drainable). Table 1 gives the values of all hydraulic properties.

The modeled area sits in a larger basin largely bounded by foothills of the Southern Annamese and Cardamom mountain ranges to the East and West, respectively, and the South China Sea to the South. An abrupt rise from the deltaic lowlands (<10m elevation) to highlands >20m elevation marks the Eastern boundary of our model. There, where bedrock approaches the land surface, we assigned an impermeable boundary condition, also used on the aquifer bottom. We assume that the Mekong River, traversing the northern and western boundaries of our study area, imposes a symmetry boundary on the aquifer system; groundwater flows to and from the river but not under it. We assigned a transient constant head boundary to the Mekong River, with values determined on a monthly basis from average monthly values over the 1996-2008 period coinciding with the period of records from monitoring wells, which are well-distributed throughout southeastern Cambodia. Figure 3 displays the model area, boundaries and locations of monitoring wells.

Hydraulic head observations show spatially-variable seasonal oscillations, with no long-term decline in the majority of wells. This suggests natural forcings dominate the hydraulic response: the influence of still-limited irrigation pumping on groundwater levels appears to have been insignificant, at the regional scale, in the past (or at least through 2008, when observations end). Our initial model assigned the transient stage of the Mekong as the only forcing, which did not reproduce seasonal oscillations of hydraulic head in distant monitoring wells. These oscillations (see Fig. 3 for examples) were reproduced after exploring alternative conceptual refinements. Such refinements sought to capture these oscillations by adding recharge. Recharge is extremely limited here: though Cambodia receives ~1400mm of annual rainfall, much of it is lost as evapotranspiration (ET). The low-conductivity surficial clay aquitard further limits infiltration and recharge from rainfall and contributes to the occurrence of annual flooding, which is extensive in the modeled area.

Our simulations indicated that we could not add any significant (<20 mm/yr) recharge in the wet season (initially applied at spatially-uniform, time-varying rates throughout the domain) without causing hydraulic heads to rise above year-start levels and continue rising in subsequent years. To lower hydraulic heads to their long-term steady values, a dry season drainage process, in excess of groundwater outflows to the low-stage Mekong was needed. Other significant surface water bodies are restricted to areas between the Mekong and our nearest monitoring wells, indicating evaporation in ponds or lakes was not responsible for the more widespread observed reductions in hydraulic heads. Key to reproducing the reductions was domain-wide application of ET, with a 3m extinction depth (head-dependent flux is cut off 3m below land surface). Including additional smaller rivers in the study area as transient drains, and adjusting

222 drain conductances, elevations and seasonality (i.e., drain operative year-round or only in dry
223 season), did not reproduce head oscillations in wells distant from any river.

224 Our model simulates both the spatial patterns and magnitudes of observed hydraulic head
225 oscillations throughout the set of 49 monitoring wells by applying recharge and
226 evapotranspiration differentially to two zones. Zones were delineated by the average annual
227 extent of the flood (Marchand, 2006), with constant rates of wet season recharge and dry season
228 ET within each zone and month. On an annual basis, the modeled flood zone loses ($ET >$
229 recharge) water at a rate of ~ 8 mm/yr, and the non-flood zone gains ($recharge > ET$) at a rate of
230 ~ 5 mm/yr (averaging a gain of 0.5 mm/yr model-wide, since zone sizes differ). The contrast in
231 net loss or gain between zones is likely related to differences in vegetation coverage (higher in
232 the flood zone) and soil conductivity (higher outside of it). The zones balance water globally to
233 maintain long-term steady groundwater levels, in part by exporting water gained from the
234 Mekong.

235 After the above-testing of model forms, we adjusted recharge and ET rates, aquifer
236 hydraulic conductivity and storage properties (within the established range) to best fit
237 observations. The mean squared error between calculated and observed heads in the base case
238 period, before pumping is assigned, is 0.62m, which is comparable to the uncertainty of surveyed
239 elevations for these wells (± 0.5 m, IDE, 2005) and the interannual variability (~ 1 m on average)
240 of monthly measurements.

241 Surface water flows in the interior domain (instream and flood) were not explicitly
242 simulated in this model, however, groundwater-surface water interactions are accounted for in
243 our transient head Mekong River, recharge and ET boundary conditions, through which fluxes of

water are simulated. These fluxes, in conjunction with aquifer system properties, give rise to the observed perturbations in hydraulic heads, which are well represented in our model. Our extensive testing of model forms, along with data-driven parameter constraints, indicate we have captured the important physical hydrogeologic processes of this system. As is best-practice in hydrogeologic modeling, in particular for data-scarce, regional aquifer systems, we have elected the simplest model form that reproduces the major spatial and temporal characteristics of the data (Voss, 2014).

Groundwater pumping was assigned, for the first simulated year of irrigation, using the irrigated area in 2011 in each commune determined from the GEE analysis, divided among the minimum necessary 1 km² cells in each commune needed to fit the GEE-determined irrigated areas. Each year, growth of these areas at the GEE-determined commune-specific rates was allowed up to an upper limit of the commune's wet season rice-planted area (as reported in the agricultural survey). At the end of the 25-year period, 20% of communes located within the boundaries of our groundwater model have reached their upper limit of rice cultivation area and 40% of all viable land across communes is projected to be under dry season production. Pumping rates were determined by multiplying these areas by the month-specific irrigation requirements, calculated by the procedure discussed in detail above. We did not simulate return flows of pumped groundwater to the Mekong or aquifer. Non-consumed water removed from the groundwater system is unlikely to return to it: base case simulations indicate that recharge in this landscape, which receives a high amount of annual rainfall and is subject to widespread flooding, is extremely limited. The average 20m thick shallow clay aquitard limits return flow to the aquifer of infiltrated irrigation water.

Results, including hydraulic heads and groundwater flows among sources and sinks, were collected from each simulated scenario. Scenarios bracket the range of irrigation water requirement, which determines minimum and maximum rates of pumping, and a reasonable range of aquifer specific yield values (0.05-0.20).

3. Results

We present three types of results. The first is quantifying the dry season deficit area in the Cambodian Mekong River catchment, or area of land cropped in the wet and not in the dry season, as estimated using the two data sources: the recent agricultural survey and the satellite imagery. The second is the expansion of groundwater-irrigated areas in southeast Cambodia, where the largest and most widely used groundwater system is located and where data are available to model it. The third pair of results derives from simulation of dry season irrigation expansion at the current rates over the next 25 years, including 1) the drawdown of groundwater levels, and 2) time-varying proportions of different water sources making up the total groundwater volume extracted by pumping wells.

The first result, quantifying the Cambodian dry season deficit area for 2009, is shown in Figure 1. In the left panel (Fig. 1A), the deficit area is calculated from survey data according to the difference between wet and dry season cultivation. The wet season rice-cultivated area reported for 1,342 communes within the Cambodian Mekong River catchment, totaled 32,197 km² (~18% of the area of Cambodia) in the 2009 agricultural survey. The dry season planted area amounted to 7,994 km², of which 4,669 km² were classified as post-flood “recession” rice (i.e., planted as floodwaters recede). The residual 3,325 km², or 10.3% of the wet season planted area requires some other source of partial or full irrigation. Because not all dry season planted

areas are double-cropped (some are single-cropped with recession rice), we calculate the deficit dry season area only for communes ($n = 1,006$) in the catchment where rice-planted areas are greater in the wet than in the dry season. By this method, the dry season deficit area is 30,281 km^2 , or 95.8% of the wet season planted area in 2009. Fig. 1B shows the estimate of the dry season deficit area according to our analysis of MODIS data (250m resolution, or 0.0625 km^2 pixels), which indicates that in 2009 the dry season deficit area was 31,093 km^2 . The percent difference is 2.7% between the agricultural survey and our analysis.

Different errors are associated with each of the two estimation methods. The survey may over- or under-report planted areas in spatially variable ways. Our satellite-based analysis does not discern fallowing of fields planted with rice compared with other crops, or dieback of wet season vegetation, and may over or under-estimate crop coverage in mixed pixels. Indeed, interannual satellite-based estimates of the dry season deficit area have a coefficient of variation, defined as the standard deviation divided by mean, of ~24% value over the period of analysis (2003-2015). This is likely a convolution of variability in cropping patterns and analysis errors. Nonetheless, there is generally good agreement in both the magnitude and spatial patterns (see Fig 1) of dry season fallowed land in Cambodia.

The second result, expansion of groundwater-irrigated land, is shown in Figure 2, which focuses on the Mekong Delta and surrounding areas of southeast Cambodia. Here finer-resolution (30m) analysis of LANDSAT data shows the proliferation of irrigated land in recent years. Over the period 2004-2011, the area of dry season planted area likely irrigated with groundwater in a given commune expanded at annual rates of up to 61% (mean: 11%, see Fig. 2A). Rates are lowest in areas proximate to the Mekong River where post-flood recession rice dominates. Rates are highest in areas bordering 1) the zone of recession rice production, and 2)

Vietnam. A typical spatiotemporal pattern of expansion (Fig 2B.) shows individual fallow fields converting to cultivated ones in growing clusters. Ground-control points visited in 2010 (white circles in the south) confirm the irrigation of rice by motorized tubewells.

Finally, we present projected decline of hydraulic heads, groundwater levels, due to expansion of pumping for irrigation in southeast Cambodia. In the base case simulation period prior to pumping, hydraulic heads in the aquifer oscillate seasonally in response to river stage, recharge and evapotranspiration. Some of the simulated monitoring locations “go dry” at the peak of the dry season, defined by reaching a high upper limit of 8m lift capacity, meaning that suction lift pumps could not extract water from those wells during this period. That wells already go dry during some portion of the year has been reported previously (IDE 2005, Johnston et al., 2013). Simulated irrigation pumping exacerbates this condition, leading to additional wells drying up in as few as two years and remaining dry year-round over large regions in as few as 5 years. At the end of the 25-year simulation period, 8,486-12,066 km² exceeds the suction lift threshold or 43-60% of the modeled area. This “dry well area” (see Fig. 4) amounts to 75-86% of the modeled area in Cambodia and 16-39% in Vietnam.

The map of depressed hydraulic heads (i.e., drawdown) and dry areas associated with the best (minimum pumping, maximum specific yield) and worst (maximum pumping, minimum specific yield) case scenarios are shown in Figure 4. Pumping pirates recharge and drains water from aquifer system storage. It also induces greater inflow from the Mekong River (see Figure 5). Compared with the base case, flows to the groundwater system from the Mekong are 4-35 times higher under future pumping scenarios.

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.

Fig. 2. Expansion of groundwater-irrigated areas in southeast Cambodia. **A.** Annual growth rate (2004-2011) of LANDSAT 5, NDVI-bright areas in February, aggregated by communes of the region. Extent of the groundwater model domain (gridded area) is also shown. **B.** Expansion of groundwater-irrigated areas over time (green). White circles show locations of ground-control measurements where groundwater irrigation of rice was observed at same time of imagery collection.

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	Parameter	Value or range	Units	
Aquitard	Hydraulic conductivity (K)	8.64E-04	m/d	354
	Specific storage	2E-04	1/m	
	Specific yield	5E-03	[-]	
Aquifer	Low K	0.7	m/d	355
	Mid K	7	m/d	
	High K	70	m/d	
	Specific storage	2E-05	1/m	356
	Specific yield	0.05-0.2	[-]	

Tab. 1. Hydraulic properties used in groundwater system simulation model.

Fig. 3. *Left:* Groundwater model domain, illustrating boundary conditions, average annual extent of flooding, zones of low, mid and high aquifer hydraulic conductivity (“K”, see Table 1. for values), and locations of monitoring wells. *Right:* Example hydrographs illustrating variability in seasonal groundwater levels throughout the domain.

Fig. 4. Best (left) and worst (right) case simulated scenarios for aquifer hydraulic heads (elevation of water table), during 25-year simulation period. Major areas where wells would remain dry year-round are outlined in orange. Dry season irrigated areas where pumping occurs are shown at far right.

Fig. 5. Cumulative water budget at the end of each 5-year period in the best (left) and worst (right) case simulated scenarios. Stacked bar height indicates the total volume pumped. At the end of 25 years total volume pumped is 7.6 and 14.9 km³, respectively. Stack components indicate the sources of water that meet pumping demand, either by replacement (recharge, river exchange), or by aquifer depletion (storage). Best case corresponds to the least pumping and highest groundwater storage estimate, and worst case to the highest pumping and lowest groundwater storage estimate.

4. Discussion and conclusions

Expansion of irrigated rice production in Cambodia to increase food security and exports would have significant consequences for transboundary water resources. The dry season deficit area, or area of land that could be double-cropped in Cambodia's Mekong river catchment, amounts to ~96% of land planted during the wet season. Much of the dry season deficit area lacks irrigation water. If this entire area were irrigated for rice, it would require up to 31% of dry season instream flows of the Mekong River and its major distributary, the Bassac, at the Vietnam border (based on mean monthly flows reported in Tri (2012), our estimated deficit area and irrigation water requirements). If canal diversion conveyance losses of 25% (Phengphaengsy and Okudaira, 2008) were included, the dry season instream flow diversion equivalent could be

as much as ~40%. In either case, the loss would be felt most significantly downstream in Vietnam, where an elaborate system of canals is fed in large part by flows from the Mekong and its distributaries. While complete conversion of dry season fallowed land to irrigation for rice is unlikely, rice cropping intensity averages 1.6 in the Vietnamese Mekong Delta (Minot and Goletti, 2000). Our upper bound estimates on flow diversions suggest that any similar changes to rice cropping practices in Cambodia would have non-trivial downstream impacts. Other higher-valued crops, which may use less water, do not occupy nearly as much area.

In the Mekong Delta, spanning both countries, groundwater reserves are abundant, but readily susceptible to overdraft. We estimate that ~45-180 km³ of groundwater is stored in the top 100m (current maximum well depth; over 80m below sea level) on the Cambodian side of the aquifer system. This reserve is essentially fossil water; high rates of evapotranspiration, and limited infiltration through surficial clays suggest, and our simulations confirm, that recharge is extremely limited (<20 mm/yr). Although the aquifer contains the volume of water needed to irrigate a dry season crop at present expansion rates over a long-term (up to ~15 km³ needed over 25 years, or as much as one-third of stored accessible groundwater), extracting it would entail significant shorter-term costs. Pumping reduces groundwater levels below accessibility limits for suction lift wells on a seasonal basis in less than 5 years, and year-round in less than 10 years. Such wells are a crucial source of clean water for domestic supply, where they do not contain naturally-occurring arsenic (e.g., Berg et al., 2007), during both wet but especially dry seasons, for >1.5 million people living in southeastern Cambodia who rely on groundwater for domestic needs (CLEAR, 2012). Falling groundwater levels also raise the costs of pumping for all users. Both consequences, in greatest part caused by wealthier users with motorized wells and resources to pump, disproportionately impact the poorest users (Sekhri, 2013). Such “*resource*

capture by elite” is an important source of water supply vulnerability (Srinivasan et al., 2012) around the world.

Intensive development of groundwater resources and sustained use pose a larger set of potential internal and international hazards. The transboundary aquifer system underlying the Mekong Delta is already over-exploited in parts of Vietnam, exacerbating arsenic contamination and causing land subsidence (Erban et al., 2014, Erban et al., 2013). Subsidence in turn affects the extent and duration of flooding, putting new limitations on rice production areas and risks to infrastructure. Excessive pumping in Cambodia, even from the shallow aquifer, which is confined by tens of meters of clay, could lead to the same consequences there, and compound such problems in Vietnam. Extraction from deeper aquifers is similarly ill-advised, and less likely to catch on in the near-term as Cambodian wells are shallow. Both countries may also experience changes in the temporal availability of Mekong River flows due to upstream damming, with potential repercussions for additional groundwater demand not considered in this study.

Given the widespread reliance of large populations in Cambodia on groundwater for domestic purposes, and the hazards associated with irrigation dependence that causes groundwater mining, high-volume extraction activities should be discouraged. Where quality is adequate, groundwater can meet human consumption needs without needing treatment, filling a void that cannot be readily met by alternative supplies. Expanded reliance on groundwater for dry season rice cultivation is not sustainable; although it may provide a narrow range of immediate benefits for some users, a broader set of long-term consequences undermine these benefits and public water supply needs. However, given that groundwater use will likely continue to rise, it may be reasonable to direct such development towards low-volume extraction

for high-value agricultural activities. A rigorous consideration of such activities, and their associated cost-benefit balances is beyond our scope, and will depend largely on local conditions. In general, land-use development in the region should be regulated by the availability of existing or readily stored surface water supplies, with groundwater reserved for low-volume, high-priority uses to conserve this vital resource. The current trajectory reveals that future groundwater resource capture by elite farmers is a significant source of vulnerability as Cambodia moves to expand irrigated agriculture.

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