The Role of Depleting Groundwater in Global Food Production

Karen Villholth, IWMI, South Africa, k.villholth@cigar.org
Aditya Sood, IWMI, Sri Lanka, a.sood.cigar.org
Nirosha Liyanage, IWMI, Sri Lanka, n.liyanage@cgiar.org
Tingju Zhu, IFPRI, Washington DC, t.zhu@cgiar.org
Yoshihide Wada, Utrecht University, Netherlands, y.wada@uu.nl

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Abstract

Globally, a significant fraction of food production derives from groundwater in irrigated agriculture. The virtues of groundwater is however, progressively turning into environmental and socio-economic burdens around the world where groundwater is being abstracted at rates beyond its natural replenishment. This groundwater depletion potentially also impacts food production and global food security as previously productive land is either turned into non-productive or returned into rainfed agriculture. The current work presents for the first time a global estimate of the contribution of depleting groundwater to global food production. Based on an integrated GIS analysis combining global distributed datasets on groundwater depletion, irrigation, and food production for the year 2005, the results indicate that between 14 and 17 percent of global groundwater irrigated food production, between 6.0 and 7.0 percent of global irrigated food production, and between 1.8 and 2.2 percent of total food production (including rainfed) is derived from depleting aquifers. This production occurs primarily in arid and semi-arid areas with good sub-surface water storages, with the South Asia, East Asia, OECD, and Near East/North Africa regions as dominating. Crop-wise, it is found that while cereals and sugar crops exhaust most groundwater, crop groups like roots and tubers, non food crops (mostly cotton), leguminous crops, and vegetables and fruits are disproportionally grown by depleting groundwater. The results imply the critical importance of analysing and developing congruent policies at multiple levels that account for the nexus between groundwater and food security.

Methodology

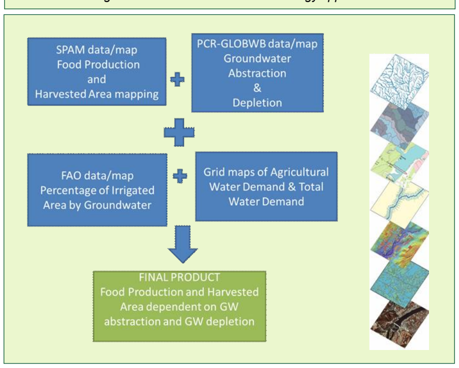
We used four global distributed datasets for our analysis: 1. Spatial Production Allocation Model (SPAM) 5 arc min. spatial resolution data from 2005 on cultivated area, harvested area and crop production (wet weight) for 42 crops for irrigated and various rainfed cultivation forms (high inputs, low inputs and subsistence production) (Anderson et al., 2014, HarvestChoice, 2009); 2. Food and Agriculture Organization of the United Nations (FAO) 5 arc min. spatial resolution data from 2005 on area equipped for irrigation and percentage of this area equipped for groundwater irrigation (Siebert et al., 2010); 3. PCRaster Global Water Balance (PCR-GLOBWB, Wada et al., 2012)) 30 arc min. spatial resolution model data from 1960-2000 on groundwater abstraction and groundwater depletion, the latter determined through 10,000 realizations of Monte Carlo runs to capture range of uncertainty (unpublished); and 4. Agriculture water demand and total water demand. This dataset, which provide global monthly water withdrawals for agriculture and total water demand, were provided by Utrecht University .

The methodology combined these datasets in a spatial (GIS-based) analysis to estimate the share of global food production (total, irrigated) derived from groundwater abstraction and groundwater depletion. Groundwater depletion in this context is defined as the case when groundwater abstraction is greater than groundwater recharge, including return flows.

The analysis process consisted of the following nine sequential steps (Figure 1):

1. The SPAM dataset was processed to aggregate the three rainfed categories (high, medium and low intensity) into one rainfed category, in terms of cultivated area, harvested area and production.
2. The SPAM irrigated dataset (cultivated area, harvested area and crop production) was further disaggregated and attributed to groundwater-irrigated and surface water irrigated parts (assuming only those two types of irrigation water sources) by comparing the SPAM total irrigated area with the FAO map of area irrigated by groundwater and using a set of logical decision rules. If the FAO map shows some area in a grid cell as groundwater-irrigated and the SPAM cell has a larger irrigated area, then it is assumed that the excess area in SPAM is surface water irrigated. If the irrigated area in SPAM's cell is less than FAO (or zero), SPAM's area is used (and the difference is assumed to be an error). Conversely, if there is no groundwater-irrigated area shown in the FAO map, but SPAM irrigated map shows irrigated area, it is assumed that the irrigation is from surface water. In this way, the final total groundwater-irrigated area as well as the total irrigated area never exceeds the total area in SPAM for irrigation. The fraction of groundwater-irrigated area to total irrigated area was estimated and applied to estimate the fraction of irrigated cultivated area and irrigated harvested area attributable to groundwater irrigation for the 42 crops (Step 6).
3. Proportion of groundwater abstraction and depletion attributable to irrigation was estimated by multiplying the abstraction and depletion rates with the proportion of water demand from agriculture to total water demand from all sectors.
4. Data on groundwater abstraction and depletion from irrigation from Step 4 were downscaled from 30 min. to 5 min. spatial resolution by cross-checking with the groundwater irrigated map (Step 2). If there is groundwater abstraction for agriculture in a 30 min. cell and there were more than one cell showing groundwater-irrigated crops in the corresponding array of cells in the better-resolved groundwater irrigation map, the groundwater abstraction/depletion is proportionally distributed among the cells based on their groundwater-irrigated fractional area. Any other combination is either an error or assumed to be due to groundwater agricultural abstraction for non-irrigation use.

Figure 1. Schematic of GIS methodology applied



At this point, the following data exist for each 5 min. cell: cultivated area, harvested area, and crop production per crop split into irrigated and rainfed for 42 crop (Step 1), groundwater-irrigated and surface water irrigated area (Step 2), groundwater abstraction and groundwater depletion from irrigation (Step 5).

5. Groundwater-irrigated fractions of irrigated cultivated area, and irrigated harvested area for each crop were determined by scaling with the cell-wide proportion of groundwater irrigation (Step 2), assuming the crops have similar distribution between groundwater and surface water irrigation. It is also assumed that all crops in a cell having groundwater irrigation were partially groundwater-irrigated. For the crop production, the amounts attributable to groundwater irrigation and surface water irrigation were estimated assuming a crop water productivity of groundwater twice that of surface water (Shah, 2007) due to higher reliability of groundwater and consequent higher investments in other crop inputs, like fertilizers, pesticides, and seeds (FAO, 2003) and the share of crop water volumetric use from groundwater equal to the cell-wide share of groundwater-irrigated area.
6. The groundwater abstraction (GWA) and groundwater depletion (GWD) from irrigation in each 5 min. cell (Step 5) were distributed to the various crops relative to the groundwater-irrigated harvested area (Step 6) occupied by each crop and taking into account the variation in crop water demand among the crops, using the following equation (here exemplified by the GWA):

$$[illegible]$$

where c is crop, n is number of crops (n=42), A is groundwater-irrigated harvested area and Kc is the crop coefficient. We used regionally uniform crop-specific crop coefficients.

7. The harvested area and crop production attributable to groundwater depletion were determined from the total groundwater-irrigated harvested area and production (Step 6), using the fraction of groundwater depletion to abstraction (always less than 100 %) (Step 5).
8. The data for the 42 crops in terms of cultivated area, harvested area, and crop production (also disaggregated into the shares by rainfed/irrigated, surface water/groundwater-irrigated, and groundwater irrigated and depleted) were aggregated into nine major crop groups, of which one was "non-food crops" and another was a residual "other crops", both constituting 1%, in terms of total production.
9. In the final step, the data were aggregated into nine global regions.

Results

Groundwater irrigated areas globally comprise about 83.1 mill. ha, or about 41% of total irrigated areas. Of the groundwater irrigated areas, 15.5 to 18.5% are supplied by depleting groundwater. In terms of global food production, groundwater irrigated food production constitutes 43.5%, and the part from depleting groundwater amounts to 14 -17% of global groundwater irrigated food production, between 6.0 and 7.0 percent of global irrigated food production, and between 1.8 and 2.2 percent of total food production (including rainfed) (Table 1).

Table 1. Contribution of groundwater and depleting groundwater to global food production

Production	Of Total (Rainfed & Irrigated)	Of Irrigated	Of Irrigated by GW
From abstracted GW	13.0%	43.5%	
From depleted GW	1.8-2.2%	6.1-7.4%	14.0-17.0%

Table 2 indicates the regional distribution of global food production from groundwater depletion (GWD). It can be seen that South Asia, OECD, East Asia, and Near Eat/North Africa dominate and account for 44.7, 23.9, 22.3%, and 8.0%, respectively (in total 98.8%) of global food production from GWD. From Table 2, it is also apparent that the dependence on depleting groundwater for food production is particularly high in South Asia and Near East/North Africa, where 6.8 and 5.3%, respectively, of total food production in these regions derive from depleting groundwater, compared to other regions where this figure is generally less than 2%. This illustrates the aridity and increasing water stress in these regions.

Table 2. Regional distribution of food production from groundwater depletion

	Food production (10^6 t)				Food production from GWD as a fraction of	
Region	From GWD	From GWD (% of total)	From irrigation	From irrigation and rainfed	Irrigated production	Total production
Australia/Oceania	0.06	0.0%	28.58	96.28	0.2%	0.1%
Central Asia	0.12	0.1%	23.57	151.96	0.5%	0.1%
East Asia	30.55	22.3%	595.02	1997.86	5.1%	1.5%
Latin America and the Caribbean	0.66	0.5%	287.38	1063.58	0.2%	0.1%
Near East/North Africa	10.94	8.0%	113.04	207.72	9.7%	5.3%
OECD	32.77	23.9%	310.35	1593.73	10.6%	2.1%
Other European Countries	0.56	0.4%	16.09	277.09	3.5%	0.2%
South Asia	61.32	44.7%	605.73	904.33	10.1%	6.8%
Sub-Saharan Africa	0.20	0.1%	62.76	518.41	0.3%	0.0%
Total or average	137.17	100.0%	2042.52	6810.96	6.7%	2.0%

In terms of crop distribution of global food production from GWD, Table 3 shows that cereals and sugar crops dominate, with 44.0 and 31.4%, respectively (in total 74.4%) of global food production from GWD. Certain crops appear to be preferentially grown with groundwater, like roots and tubers, non-food crops (mostly cotton), leguminous crops, and vegetables and fruits. Their share of production from GWD is 14.2, 9.8, 9.1, and 7.8%, respectively, as compared to an overall average of 6.7% for all crops. This is consistent with what is found in the literature, and is explained by the high market value of most of these crops, commensurate with groundwater providing reliable irrigation water supply (Shah, 2007).

Table 3. Crop distribution of food production from groundwater depletion

	Food production (10^6 t)				Food production from GWD as a fraction of	
Crop group	From GWD	From GWD (% of total)	From irrigation	From irrigation and rainfed	Irrigated production	Total production
Beverages	0.00	0.0%	0.63	15.32	0.0%	0.0%
Cereals	60.41	44.0%	902.23	2260.27	6.7%	2.7%
Leguminous crops	0.85	0.6%	9.25	60.63	9.1%	1.4%
Non-food crops	4.03	2.9%	41.16	82.64	9.8%	4.9%
Oilseed crops	2.65	1.9%	42.91	593.75	6.2%	0.4%
Other crops	0.32	0.2%	1.68	29.60	19.0%	1.1%
Roots and tubers	15.45	11.3%	109.17	723.58	14.2%	2.1%
Sugar crops	43.04	31.4%	801.26	1613.48	5.4%	2.7%
Vegetables and fruit	10.48	7.6%	134.21	1431.70	7.8%	0.7%
Total or average	137.21	100.0%	2042.50	6810.97	6.7%	2.0%

The results provide important insight to inform global and national strategies for curbing groundwater depletion while sustaining food security.

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