and there are challenges with all possibilities, there is need for a vigorous debate on the appropriate approach to satisfy this need; policy-makers need to be aware of such information before making decisions on long-term energy strategies that may lock options for the country.

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Groundwater loss in India and an integrated climate solution

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In the developing world climate change has far more ramifications than can be addressed by controlling just carbon emissions. The developed world has stable populations and landscapes, and is thus affected mainly by the air which spreads democratically without boundaries. On the other hand, the developing world with increasing populations and consumption is depleting its living natural resource base of water, forest, soils and agriculture, and is poised for a far greater catastrophe. In fact, more and more regions in overpopulated Asia and arid Middle East and North Africa are heading into a water crisis. The developing world needs an integrated solution that addresses water, agriculture and forests. We work out such a solution with India as a case study.

NASA's gravity mapping satellite 'GRACE' tracks the local gravity field of an area below it. If we take out a lot of groundwater from such an area, there is a loss of mass and it shows up as reduced gravity. Recent reports[1–4] based on GRACE satellite data show that in a large and fertile area of North India, about 440,000 sq. km, groundwater levels have been going down by 30 cm (or 1 ft) of water a year from overdrawing. A 30 cm (or 1 ft) drop in groundwater level is equivalent to a 4 cm loss of raw water. This area has lost an average of about 18 km^3 of water/yr, which means a loss of 4 cm of raw groundwater per year. Since this has been going on for more than 30 years, over 1.2 m of raw water has been lost. Alternatively, groundwater levels have declined by an average of 10 m. However, this is not the real loss. A lot of the area surveyed by GRACE that is not cultivated, has not lost water. It is in the cultivated area, that accounts for over half of the region that is mapped by the satellite, that the loss is concentrated. In what follows we estimate the water loss for the cultivated area using ground agricultural data.

Water loss in the cultivated area

In the total area monitored by the satellite, the cultivated area accounts for a little over half the area (about 240,000 sq. km). Now we present a more grounded estimate of water loss based on agricultural water use. The cultivated area on the map of this region includes Punjab, Haryana, western Uttar Pradesh (UP) and parts of Rajasthan, which is the granary of the India (western UP has, perhaps inadvertently, been left out in the paper by Rodell *et al.*[1], see Figure 1). It produces much of the irrigation-intensive rice, sugar cane and wheat apart from the less irrigation-intensive pulses, millet, etc.

Rice and sugar cane need over 60 cm of raw water and wheat over 30 cm. Usually, there is a dual cropping pattern of rice in the monsoon season and wheat in the winter–spring. This requires over 100 cm of water annually[5].

From the official data, the water-intensive rice[6–9] and sugar cane[10] growing areas in this swathe of land amount to about 100,000 sq. km. For rice, the division is as follows: 27,800 sq. km under rice in Punjab and 10,800 sq. km under rice in Haryana. All of UP has 46,000 sq. km under rice, of which western UP has the high and medium productivity rice areas ~30,000 sq. km and Rajasthan has 1800 sq. km. Sugar cane is mainly grown in western UP which has 20,540 sq. km under sugar cane[10].

The rest, 140,000 sq. km, grows millet, pulses and wheat[11]. For areas which do not grow rice or sugar cane, the annual water needs are approximately 50 cm/yr.

Thus the weighted average requirement for the area under agriculture is about 71 cm of water/yr. Return flow data[12,13] suggest that of this about one quarter seeps back to the ground.

Now, about 60% of the cultivated area is serviced entirely by groundwater[14,15]. Let us see what are the implications for the groundwater regime once we are armed with this knowledge. In passing, we note that the groundwater table goes down with groundwater draft but goes up from seepage in canal irrigation.

The cultivated area divides into two lots. The area irrigated by groundwater, about 60% of the cropped area,

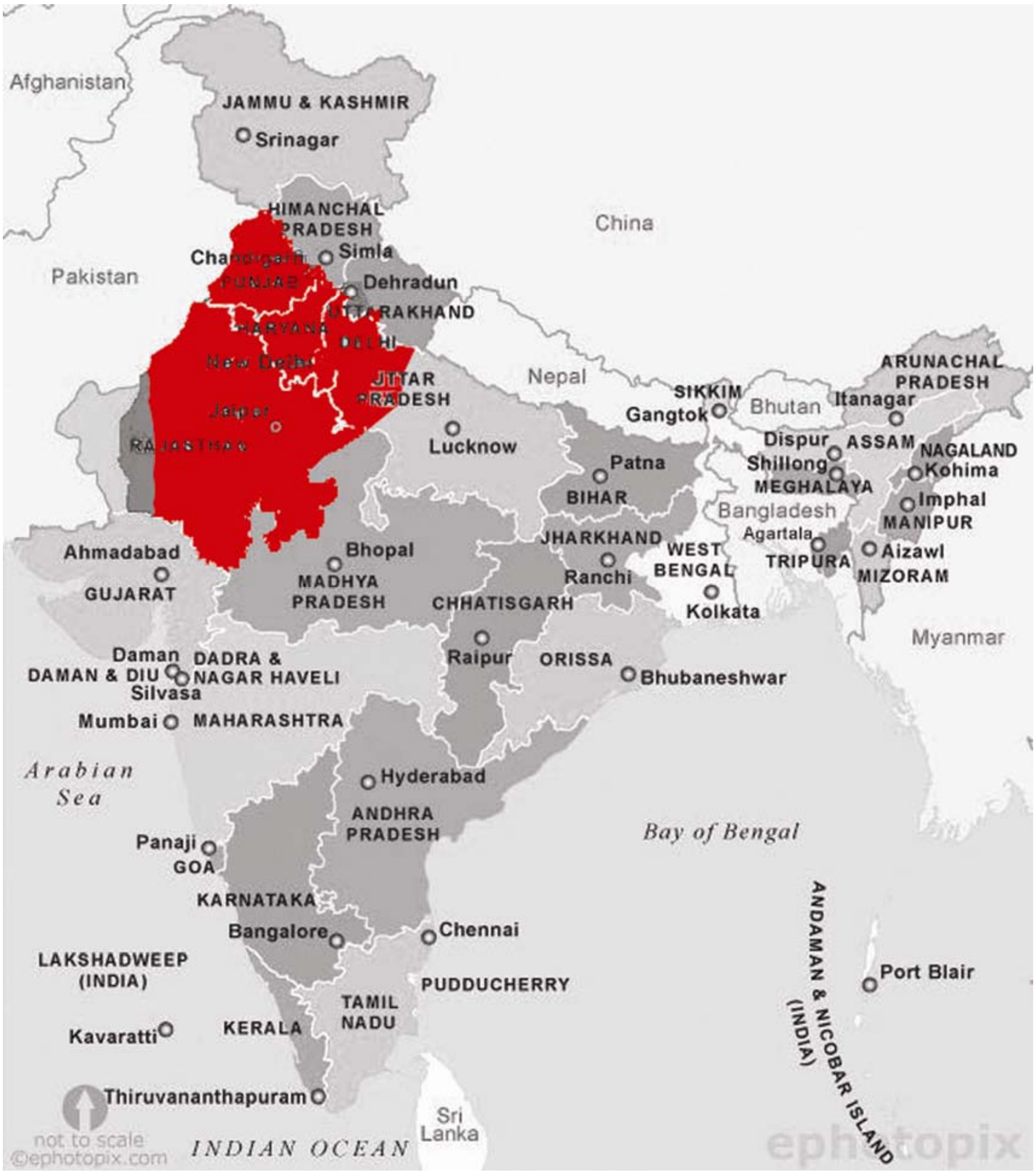

Figure 1. The area marked in red is a rough demarcation of the area surveyed.

effectively uses 71 cm of drawn groundwater. About a quarter of this, 17 cm of the water, is sent back into the ground as return flow. We use the national average of 12 cm of water (probably an overestimate) for natural rain recharge. For the groundwater irrigated area this works out to an annual deficit of 42 cm of water. This means an annual reduction of 61 km^3 of groundwater from this area.

For the remaining 40% (likely to be less) of canal-irrigated area, 17 cm is added to the ground from irrigation return flow recharge and 12 cm from natural recharge, giving a total of 29 cm. This implies an annual addition of 28 km^3 of groundwater from this area.

For 200,000 sq. km of the area which is not cultivated and arid, we can expect a maximum recharge of 10 cm. Of this, 20% can be set aside for domestic and industrial use, leaving 8 cm of groundwater addition. This means an annual increment of 16 km^3 of groundwater from this area.

Results

If we now look at the water budget for the whole area, it is not so different from the GRACE data which give an average loss of 17.7 km^3 of water/yr, in comparison to our estimate of 17 km^3/yr.

But if we consider the total cultivated area of about 240,000 sq. km, there is an annual deficit of 33 km^3 of water, translating into annual average loss of 14 cm of raw water, 3.5 times what is naively gleaned from the averages for the whole land surveyed by the GRACE satellite. This implies that in 30 years the loss would be 4.2 m of water or 30 m of groundwater level. Most aquifers are not that deep; so it means we are approaching a swift end to the resource.

It will take several decades to recover from this loss.

Discussion

Agriculture – natural wisdom

Groundwater-based agriculture brings down groundwater levels considerably, whereas canal irrigation adds to groundwater levels. So an ideal mix is to complement groundwater-based farming with canals or vice versa.

Here is the first lesson. Clearly it makes sense to mix canal and groundwater irrigation, as one augments groundwater by 29 cm/yr and the other diminishes it by 42 cm/yr. The area serviced by canals, about 100,000 sq. km, cannot be increased in view of the overdrawn rivers. If we use a mix of three area units of canal irrigation to one area unit of groundwater irrigation, we get an average addition of about 11 cm of water for an area of 133,000 sq. km. The remainder of the groundwatered area would have to remain fallow and will add 12 cm of natural rain recharge each year. In this case, on the average it would take 30–40 years to replenish the loss. In other words, we would have to cut down the purely groundwater cultivated area from 144,000 to 33,000 sq. km. However, the total reduction in cultivated area would be over 40%.

Forest agriculture – a solution

The balance of the groundwater irrigated area, about 106,000 sq. km, picks up 12 cm of natural rain recharge a year, and a good solution that can improve both soil and water recharge is to grow a forest on this area. The forested area will recover its water loss in 30–40 years.

With present practices in agriculture, we are likely to see a loss of a third of agricultural produce in the areas that have a water deficit. Many areas of India, like the North East, parts of West Bengal, Odisha and Jharkhand, and the Western Ghats are not water deficit. Approximately half the cultivated area in the country is water deficit[16] (by this we mean where groundwater is overdrawn). Can we use this to estimate the quantum of loss from the groundwater deficit? About 18% of India's GNP (~US$ 1500 billion) comes from agriculture. If we lose one-third of production in half the cultivated area, the loss is 3% of GNP or about US$ 45 billion a year. A substantial fraction of this is the compensation that would have to be given to farmers to grow forest, apart from the cost of sourcing for the loss of food.

We have found that with such a strategy, we can replenish water resource in about 35 years, but with a loss of about 40% of output in the water-deficit regions. Can we make this up? As a matter of fact, agriculture in India is water-inefficient and cutting down wasteful water use may save a substantial percentage of all water loss and food loss.

Forest carbon credits

It is here that climate change and carbon credits fall in like a penny into the slot. Carbon credits for forest cultivation will enthuse the farmer and at the same time get the total forest area up to the norm of a third of the country area, revive the soil and purify the water below it. This is an almost magic formula to revive lost aquifers. In addition a well managed forest industry with sustainable rotation practices will be a value added resource both for forest products and employment. Just for the record, the cultivated area in India (~1.36 million sq. km) is somewhat over one-third of the total country area. Of this close to half is water deficit[16], where we would place forests in one-third of it. This would add forest close to 6% of the total area of the country – a step in the right direction.

A simple calculation of the amount of carbon this would sequester can be made from the estimate that 3.45 million sq. km of forest plantation could fix 1.14 Gt (gigatons) of carbon a year[17,18]. Foresting 6% of India's area (3.4 million sq. km) then works out to sequestering about 0.068 Gt of carbon a year. India's total carbon emission is about 5% of the world total of about 7 Gt, and so this would sequester almost 20% of India's total carbon emissions. That is certainly worthy of carbon credits.

Forests also safeguard the quality of soil and groundwater as natural purification processes combine to cleanse the water by the time it gets to the water table. The loss of forest cover and topsoil has certainly degraded not just the quantity but also the quality of water. A major cause in the quality loss for groundwater is the leaching of fertilizers and pesticides in the soil from farming.

Water carbon credits

Let us find out if we can justify carbon credits for restoring groundwater. What happens if the water underground runs out and we have to transport it from 20 km away? Normal tankers that carry 10 m^3 of water run at 8 km/l of diesel oil. So, to make one up–down trip we need about 5 litres of diesel. Can we estimate the carbon footprint? All you have to know is that 1 litre of oil burning produces about 0.7 kg of carbon (not CO_2)[19]. So to bring in 10 m^3 of water from 20 km away hoists 3.5 kg of carbon into the air.

India has about 1.36 million sq. km of land under agriculture. We found 14 cm/yr of water deficit, on the average, for rainwater-deficit areas in northwest India, we may assume similar or somewhat smaller figures for the national water deficit areas. In this case, using the estimate that half of the cultivated area has this water deficit, implies a water deficit of around 80–100 billion m^3. The cost of transporting 80–100 billion m^3 water from 20 km away carries a diesel cost of US$ 30–40 billion.

If we have to transport this water from 20 km away, the carbon emission cost for the country works out to hoisting 0.035 Gt of carbon into the atmosphere. Transport of water to service the water deficit will work out to 10% of the present total carbon emissions for the country!

Conclusion

We have found that for the total cultivated area of about 240,000 sq. km, there is an annual deficit of 33 km^3 of water, translating into an annual average loss of 14 cm of raw water, 3.5 times of what is naively gleaned from the averages for the whole land surveyed by the GRACE satellite. For the forest agriculture scheme above, carbon credits can be claimed both for forest plantations, which will sequester carbon (20% of total carbon emissions) and water replenishment, which saves (10% of total) carbon emissions of water transport.

There is an added bonus here. Many rivers in the areas monitored above have been overexploited and suffer from very low flows. Foresting cultivated areas by rivers will make the land hold more water and release it into the rivers in the dry season to maintain ecological flows. This is evidenced from such initiatives in North Central China and Ethiopia. These are 'integrated' credits, they could change the forest and water scenario from being beleaguered to bright.

If this the expected scenario for India, it is already a grim reality in Africa, where from Ethiopia and Sudan in the east to Senegal in the west both water and agriculture and forest are fast receding. It is abundantly clear that climate-change solutions in the developing world are far more complex than just carbon emission control. If we neglect the basics like water, and agriculture and forest, the damage control exercise is going to be very dear. It makes eminent sense to look at the integrated response to climate change that we have graphed out above for the developing world.

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