The Ganges Water Machine

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The river Ganges and its tributaries, and the flat and fertile plain through which they flow, are one of earth's great natural resources. For thousands of years abundant water and generous land have provided the foundation for a highly developed civilization based on agriculture and for one of the world's largest concentrations of human populations. But farming is mainly traditional and at a subsistence level, with little surplus, and as a result the population has remained overwhelmingly rural and most people are desperately poor. Although irrigation from canals and wells has been practiced for millennia, chiefly as a protection against the uncertainties of the monsoon rains, the water resources are largely untapped; the small fraction of water used for irrigation is poorly managed and its productivity is low.

Deeply embedded cultural, social, and economic problems inhibit modernization of agriculture and fuller utilization of the water resources. Capital investments and technological changes on a large scale are also required. As experience elsewhere shows, the introduction of technological changes on the required scale might break the chains of tradition and injustice that now bind the people in misery and poverty.

Ganges and Its Tributaries

The Ganges Basin covers parts of four countries, India, Nepal, Tibet, and Bangladesh; eight Indian states, Punjab, Uttar Pradesh, Haryana, Himachal Pradesh, Rajasthan, Madhya Pradesh, Bihar, and West Bengal; and the Union Territory of Delhi. We shall consider that part of the Basin that drains into Bangladesh through the great distributary called the Padma. The other main distributary, called the Bhagirathi, has long been moribund and now serves only as a spill channel for Ganges floods. Within India, the Ganges Basin, as we have defined it, covers 800,000 square kilometers (*1*). Its population is about 225 million, somewhat more than that of the United States, which covers nearly ten times the area. At present rates of growth, the population will double in 30 years.

The fundamental problems of land and water development in the Ganges Plain arise from the highly seasonal flow of the river and its tributaries. Nearly 84 percent of the rainfall occurs from June through September, and 80 percent of the annual river flow takes place during the 4 months of July through October.

The average annual flow of the Ganges at the Hardinge Bridge in western Bangladesh is 36.2×10^6 hectare-meters, and the monsoon flow from July through October is 28.9×10^6 ha-m. During the remaining 8 months of the year, the river carries only 7.3×10^6 ha-m (*2*). Part of this dry-season flow comes from groundwater in the Ganges Plain, and the remainder comes mainly from the Himalayas.

Even at present, the dry-season flow of the Ganges is barely sufficient for the needs of India and Bangladesh. If irrigation with either groundwater or surface water continues to be developed along the lines of present programs, the dry-season flow will be continually reduced. In order to develop the full irrigation potential of agricultural land without unacceptable reduction of the dry-season flow of the Ganges, it will be essential to store a portion of the monsoon waters for use in irrigation. Because of the steep slopes of the Himalayan foothills and the flatness of the Ganges Plain, surface sites for storage are scarce, and costs per unit volume of surface-stored water are several times higher than in many other parts of the world. On the other hand, there are great possibilities for underground storage, which should be relatively inexpensive.

Present Needs for the Ganges Low Flow

Irrigation in Bangladesh. The average rainfall in Bangladesh is higher, and the potential for increasing groundwater recharge from rain is greater, than in the Indian part of the Ganges Plain. Unfortunately, there is a wide variation among different districts, just as in India. Revelle and Herman (*3*) estimated that water from the Ganges is needed in Bangladesh during the low flow season to supplement groundwater irrigation in three districts in the northwestern part of the country. In the southwest, where the groundwater is saline, Ganges water is the sole irrigation source. In other districts some Ganges water is needed to minimize saltwater intrusion. The sum of these needs totals about 1.8×10^6 ha-m.

Diversion of low flow waters for Calcutta port maintenance. Part of the Ganges waters during the low flow season must be diverted at the Farakka Barrage through the Bhagirathi into the Hooghly River, to maintain a sufficient freshwater discharge past the port of Calcutta. We learn that the feeder channel at the Farakka Barrage has been designed and constructed for a capacity of about 0.29×10^6 ha-m per month. This is more than half the average low flow of the Ganges during the 3 months of February through April. These are also the months when the need for surface water is most critical in western Bangladesh and when the flow into the rivers from groundwater is minimal.

Navigation on the main stream. Economic development in both India and Bangladesh would be hastened if the Ganges could be used as a great international waterway for transport of heavy or bulk materials. Conversely, as development proceeds, the needs for year-round water transportation on the river will rapidly grow. A water route down the Ganges and up the Brahmaputra into Assam would yield large benefits today.

Year-round transportation will depend directly on maintaining a sufficient dry-season flow. Even for relatively shallow barges and moderate-sized ships, an average river depth of 5 m would be desirable. With a width of 900 m and a velocity of flow of 0.35 m per second, this would require a minimum discharge of 1550 m^3/sec, or about 3.2×10^6 ha-m during the eight dry months.

Downstream water quality. The growth of modern agriculture in India,

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based on irrigation development, and the construction of heavy industries with large water demands will inevitably worsen the quality of the Ganges waters during the low flow season. A large variety and quantity of chemical and organic residues, including chemical fertilizers and pesticides, will be carried in the return flows to the rivers. Although it is difficult to make a quantitative estimate of the amounts that will be involved, one of the most forceful arguments for maintaining the low flow is to ensure that a sufficient volume of water remains in the rivers to dilute and oxidize these residues.

Utilization of Monsoon Flows

Taking into account the irrigation potential in the kharif (monsoon) and rabi (winter) growing seasons, at least 25×10^6 gross cropped hectares in the Ganges Plain could be fully irrigated in addition to the present partially irrigated gross area of about 12.5×10^6 hectares. With modern agricultural technology, the production of food grains from the irrigated area could be more than 150×10^6 metric tons, enough to provide a satisfactory diet for more than 600 million people. These possibilities can be realized, however, only by integrated development of the surface and groundwater resources of the Ganges Basin. The time required would be of the order of 25 years, but benefits from projects which would be compatible with the integrated system could be obtained at every stage.

The key to successful development will be storage and beneficial use of a major part of the monsoon flows of the Ganges and its tributaries, which now run to the sea largely unused. Utilization of these high flows for irrigation throughout the year would have a further advantage in ameliorating flood damage (*4*).

In the past, irrigation development in both the kharif and rabi seasons has been largely based on diversion of the river flows and on utilization of a portion of the underground waters which would otherwise seep back into the rivers. The low flows of the Ganges and its tributaries are being progressively reduced, even though the present river volume during the 8 months of the dry season is just about sufficient for municipal and industrial water supply and waste disposal, maintenance of water quality, diversions to protect the port of Calcutta, needs of Bangladesh including prevention of salinity intrusion, and future needs for navigation.

Besides the limited possibilities for surface storage, there are at least five ways in which a portion of the monsoon flows could be stored underground. Infiltration into the water table in the monsoon season could be increased by (i) water spreading in the piedmont deposit north of the Terai belt of springs and marshes; (ii) constructing bunds at right angles to the flow lines in uncultivated fields to slow down runoff and increase infiltration; (iii) pumping out the underground aquifers during the dry season in the neighborhood of nallahs (natural drains) which carry water during the monsoon (*5*); (iv) pumping out groundwater during the dry season along certain tributaries of the Ganges to provide space for groundwater storage; and (v) increasing seepage from irrigation canals during the monsoon season by extending the network of canals, distributaries, and water courses for kharif irrigation and pumping out this seepage water during the dry season. In addition, evaporation losses from the water table might be reduced by lowering it below the level of appreciable evaporation. Finally, it may be beneficial to export some monsoon water from the Basin to the areas to the south and west where irrigation could be extended if firm water supplies were available.

In Table 1 we have estimated the likely increase in irrigation water supplies produced by some of these devices. A large increase could be obtained by construction of barrages and "leaky" canal systems for surface irrigation of a large part of the cultivated area, including an increased area of rice cultivation, during the kharif season, plus wells to recover the underground seepage during the rabi season. Recharge of aquifers along certain Ganges tributaries could provide an equally large increase of rabi irrigation supplies.

Possible use of aquifers near rivers to store monsoon water. There is good reason to believe that in many places the underground aquifers are well connected to the rivers and are highly permeable. For example, in one region where a groundwater survey was made (*6*) the seasonal contours of the water table on both sides of a large tributary show that this river is a drain which carries off perhaps 0.12×10^6 ha-m of water that seeps into it during the dry months from the underground aquifers. If these contours could be reversed by large-scale pumping of the underground waters in the dry season, the aquifers could receive and store a large part of the monsoon flow of the river. We believe that similar underground storage of river floodwaters could be carried out along many tributaries of the Ganges.

It would be necessary to lower the

Table 1. Possible future water budget for the Ganges Plain. Except where noted, values are calculated from data in *Report of the Irrigation Commission, 1972* (*1*).

Source or sink	Volume ($\times 10^6$ ha-m) during	
	Low flow season (November to June)	High flow season (July to October)
Supplies		
Present average river flow at Bangladesh boundary	7.3*	28.9*
Evapotranspiration from present surface storage and river diversion (1968–1969)	1.8†	1.8†
Evapotranspiration from present well irrigation (1968–1969)	1.3†	0.7†
Additional surface storage (under construction or potential)	1.5	−1.5
Reduction of groundwater evaporation by pumping down water table	0.8†	
Increased infiltration of rainfall by bunding in uncultivated areas	0.7†	−0.7†
Potential additional underground storage	6.0‡	−6.0‡
Transfers out of basin (such as "Ganga-Cauvery Link")		−1.8
Total supplies	19.4	21.4
Uses and excess flows		
Consumptive use in present irrigation (1968–1969)	3.1	2.5
Consumptive use in potential additional irrigation	9.0†	6.0†
Diversion to Hooghly River at Farakka Barrage for Calcutta maintenance	2.3‡	
Needs for irrigation in Bangladesh	1.8‡	
River navigation and waste disposal	3.2‡	
Monsoon flow at Bangladesh boundary§		12.9
Total uses and excess flows	19.4	21.4

* From (*2*). † See (*9*). ‡ See text. § Estmiated by differences.

water table to a greater depth at the beginning of the monsoon season than that required simply to produce the storage volume. Moreover, the aquifer directly under the river would need to be pumped down close to the average depth. In the rivers of the western part of the Plain, where the dry-season flow comes largely from groundwater seeping out of the river banks, the low flow discharge during the first year would be removed by the pumping, and thereafter the river would be virtually dry during the months of November to June. Several years would be required to obtain the full storage potential. Each year the water table at the beginning of the monsoon season would be pumped deeper than the year before, until an equilibrium would ultimately be reached.

Pumping out Groundwater during Low Flow Season

For a rough estimate we may assume that along 3200 km of the system of larger tributaries of the Ganges (about a quarter of the total length) large well fields could be constructed which would produce storage space by pumping out the groundwater during the low flow season. With well fields 6 km wide on either side of the river, the area covered would be 3.8×10^6 ha. If we assume that the well field capacity is 2.25 m^3/sec per kilometer (that is, 1.12 m^3/sec on each side of the river per kilometer of length) and the storage coefficient of the aquifer is 0.25, then the water table will be lowered, on the average, about 12 m at the end of 8 months of continuous pumping. All the wells need not be of the same capacity. It is necessary only to design the well spacings and discharges in such a way that we pump out a trough of 12 m below the river bed. The method used for finding the depression of the water table is given below.

The drawdown due to pumping in an aquifer is given by

$$s = \frac{Q}{4\pi T}\int_{\frac{r^2 S}{4Tt}}^{\infty}\frac{e^{-u}}{u}\,du \qquad (1)$$

where the drawdown $s = h_i - h$ (m), h_i is the initial saturated thickness of the aquifer (m), h is the height of the water table during pumping (m), Q is discharge (m^3/day), T is the coefficient of transmissibility (m^2/day), S is the storage coefficient (dimensionless), t is time since pumping started (days), and r is the distance from the pumping well (m).

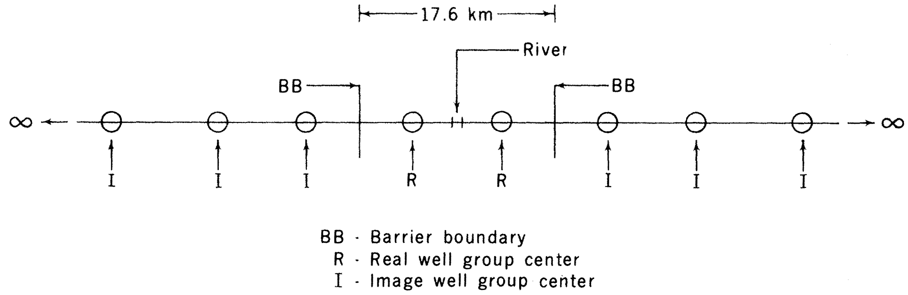

Fig. 1. Location of real and image well groups.

Equation 1 holds strictly only for a confined aquifer which is isotropic and homogenous. However, it can be used for an unconfined water table aquifer (as in the present case) provided drawdown is small compared with the original saturated thickness of the aquifer. In the Ganges Plain the aquifers are quite thick, and the drawdown of the water table will be small compared with the initial saturated thickness of the aquifer; consequently, we can apply Eq. 1. There are other assumptions involved in the derivation of Eq. 1. Revelle and Herman (*3*) showed that, although these assumptions are not strictly valid in the present case, the equation can still be used to give a fairly good solution.

Equation 1 is the solution of the differential equation

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (2)$$

subject to certain simple boundary conditions. Since Eq. 2 is linear, the superposition principle can be used to find the solution when more than one well is being pumped in the aquifer. Equation 1 is obtained on the assumption that the aquifer is areally infinite. If we have boundaries then we must use the method of images.

In the present calculation we have assumed that there is a natural groundwater divide at a distance of 8 km on either side of the river. This is approximately true for many of the tributaries that feed the main tributaries of the Ganges. The natural groundwater divide acts as an impervious barrier. The presence of the river itself can be ignored in the computations, since during the dry season the quantity of flow in many Ganges tributaries will be small compared with the quantity of pumping. Grouping the wells in pumping centers, we will have the real and image wells shown in Fig. 1. Because of the assumed existence of an impervious boundary on either side of the river, there will be an infinite number of images. However, only a few need to be considered, since the effect of image wells very far off will be small near the river.

Equation 1 is applied repeatedly for all the real and image wells, and we obtain a lowering of the water table, on the average, of about 12 m at the real wells.

Table 2. Possible river reaches for underground storage of monsoon flows (assuming storage of 1800 ha-m per kilometer of river). Estimated monsoon and dry-season flows are based on U.N. data (*2*).

River	Length of well fields (km)	Monsoon flow ($\times 10^6$ ha-m)		Dry-season flow ($\times 10^6$ ha-m)	Ratio of dry-season to stored flow (%)
		Stored under-ground	Remain-ing in river		
1) Ganga to Yamuna	720	1.3	0.1	0.3	23
2) Ramganga	560	1.0	0.1	0.2	20
3) Yamuna system	1440	2.6	0.3	0.7	27
4) Gumti and Sai	610	1.1	0.1	0.3	27
5) Gagra, Sarda, and Rapti	1280	2.3	3.2	1.2	52
6) Son	640	1.2	1.0	0.5	42
7) Buhri Gandak and Baghmati	720	1.3	3.2	1.0	77
8) Below the Kosi, including Mahananda	400	0.7	1.1	0.4	57
Totals	6370	11.5	9.1	4.6	42
Sum of 1 to 4	3330	6.0	0.6	1.5	25
Sum of 5 to 8	3040	5.5	8.5	3.1	56

Recharge of Groundwater Mound by Monsoon Flow

When pumping stops at the end of the dry season there is some flow into the trough from the sides. It is therefore assumed that we have a net trough with an average depth of 10 m to be partly filled by monsoon flow in the river.

The growth of the groundwater mound resulting from infiltration of the monsoon flow in the river is computed by using the following equations given by Hantush (*7*)

$$h^2 = h_i^2 + \frac{WT}{KS}t\left\{2 - 4i^2\,Erfc\left[\frac{L-x}{\left(4\frac{T}{S}t\right)^{\frac{1}{2}}}\right] - 4i^2\,Erfc\left[\frac{L+x}{\left(4\frac{T}{S}t\right)^{\frac{1}{2}}}\right]\right\} \text{ for } x < L \quad (3)$$

$$h^2 = h_i^2 + \frac{WT}{KS}t\left\{4i^2\,Erfc\left[\frac{x-L}{\left(4\frac{T}{S}t\right)^{\frac{1}{2}}}\right] - 4i^2\,Erfc\left[\frac{L+x}{\left(4\frac{T}{S}t\right)^{\frac{1}{2}}}\right]\right\} \text{ for } x > L \quad (4)$$

where the symbols other than the ones already used are: *W*, recharge rate through the bed of the river (m/day); *K*, coefficient of permeability in the aquifer (m/day); *t*, time during which recharge takes place (days); *L*, half-width of river (m); *x*, distance from center of river (m); and

$$Erf(x) = \frac{2}{\pi^{\frac{1}{2}}}\int_0^x e^{-\xi^2}d\xi$$

$$Erfc(x) = 1 - Erf(x)$$

$$4i^2\,Erfc(x) = Erfc(x) - 2x\,iErfc(x)$$

Since Eqs. 3 and 4 are implicit, a trial and error procedure or a graphical method has to be adopted for solution. For example, assume $t = 15$ days. Then, using $T = 4650$ m^2/day, $L = 150$ m, $W = 0.61$ m/day, $K = 15.2$ m/day, $S = 0.25$, $h_i = 300$ m, and $t = 15$ days, we get $(4Tt/S)^{1/2} = 1055$ m and $L/(4Tt/S)^{1/2} = 0.144$. From Eq. 3 we find

$$h^2 = (300)^2 + \left(\frac{0.61}{15.2} \times \frac{4650}{0.25} \times 15\right)(0.56) = 96{,}270 \text{ m}^2$$

Therefore

$$h = 310 \text{ m}$$
$$h - h_i = 10 \text{ m}$$

Thus the time for the water to rise 10 m at the center of the recharging strip is 15 days.

The height of the groundwater at a distance of 600 m from the center of the river can be computed as follows

$$\frac{x-L}{\left(4\frac{T}{S}t\right)^{\frac{1}{2}}} = \frac{450}{1055} = 0.43$$

$$\frac{x+L}{\left(4\frac{T}{S}t\right)^{\frac{1}{2}}} = \frac{750}{1055} = 0.72$$

Using Eq. 4 we obtain

$$h^2 = (300)^2 + \left(\frac{0.61}{15.2} \times \frac{4650}{0.25} \times 15\right)(0.35 - 0.14) = 92{,}350 \text{ m}^2$$

Therefore

$$h = 303.5 \text{ m}$$
$$h - h_i = 3.5 \text{ m}$$

Similarly at 1500 m, we obtain

$$h^2 = (300)^2 + \left(\frac{0.61}{1512} \times \frac{4650}{0.25} \times 15\right)(0.016 - 0.005) = 90{,}123 \text{ m}^2$$

$$h = 300.2 \text{ m}$$
$$h - h_i = 0.2 \text{ m}$$

Thus, assuming that the rate of recharge is 0.61 m/day, which is a rather conservative figure, the height of the water mound at the end of 15 days will be 3.5 m at a distance of 600 m and 0.2 m at a distance of 1500 m. From this we can compute the quantity of monsoon water abstracted as 1 $\times 10^6$ ha-m. After 15 days there will still be some recharge, because some of the bank flow from the river will continue to fill the trough. Thus, during the first year of operation somewhat more than 1×10^6 ha-m will be extracted from the monsoon flow. When this is spread over the groundwater basin 17.5 km wide, it will raise the water table by 0.75 m. To this we may add a rise of the water table by 0.6 m caused by 15 cm of net rainfall infiltrating to the water table. Thus, at the beginning of the second year of operation the water table will be about 8.6 m below the level at the beginning of the first year.

During the second year of operation the water table will be lowered by 10 m to a depth of about 18.6 m before the monsoon flow begins. The time taken to raise the water table 18.6 m at the center of the river bed during the monsoon comes to 33 days. At this time the height of the groundwater mound will be 7.5 m at a distance of 600 m and 1.5 m at a distance of 1500 m. The total quantity of monsoon water extracted will be about 2×10^6 ha-m, again ignoring the contribution from bank flow. This will raise the water table by about 1.5 m. Adding about 0.6 m due to infiltration of rainfall, the depth of the water table at the beginning of the dry season in the following year will be 16.5 m below the initial level.

During the third year of operation this will again be lowered by 10 m, leaving the water table at a depth of about 26.5 m at the beginning of the monsoon. The time taken for the water table under the river to rise 26.5 m is about 70 days. At this time the height of the groundwater mound will be 15 m at a distance of 600 m, 5 m at a distance of 1500 m, and 0 m at a distance of 3000 m. Thus, the amount of water extracted from the monsoon flow, ignoring the contribution from bank flow, will be about 6×10^6 ha-m. At the end of the monsoon the water table will be at an average depth of about 22 m over the cross section of 17.5 km.

By similar computation, we can show that during the fourth year of operation the depth of the water table at the end of the pumping season will be 32 m, and in the 120 days of the monsoon season we will extract from the monsoon about 9×10^6 ha-m. The depth of the water table at the end of the monsoon will be about 25 m below the initial level 4 years earlier.

From the following year onward, the water table will be stabilized at these levels by pumping out a quantity equal to consumptive use plus surface drainage plus return infiltration to the groundwater table.

Figure 2 shows the growth of the groundwater mound under uniform recharge from the river for the stated values of the parameters. Because different scales have been used in the horizontal and vertical directions, the slope of the water table appears to be steep. Actually its profile will be very flat. For instance, at the end of the first monsoon period the slope will be approximately 1 to 170; at the end of the fourth monsoon period it will be approximately 1 to 140. We can therefore use the bank storage equations given by Cooper and Rorabaugh (*8*) for a horizontal water table, as shown in the next section.

With any particular set of assumed parameters, equilibrium will be reached in the number of years required to lower the water table to a depth such that 120 days (the length of the monsoon season) will be required for the infiltration mound to reach the bed of the river. For example, assuming a storage coefficient of 0.15, a transmissibility of 2800 m^2/day, and a pumping rate of 1.35 m^3 sec^{-1} km^{-1}, an equilibrium depth of 35 m at the end of the monsoon season will be reached in about 12 years. From that time onward, 6×10^6 ha-m will be stored each year.

During the monsoon season the rivers in northern India always carry some water, with flood peaks occurring after every heavy storm. Thus, even if the duration of the flood wave is short, say 6 to 12 hours in the smaller streams (longer in bigger tributaries)—recharge will continue under the lesser flow that prevails before and after its passage. Hence we can assume that about 120 days is always available for recharge during the monsoon season.

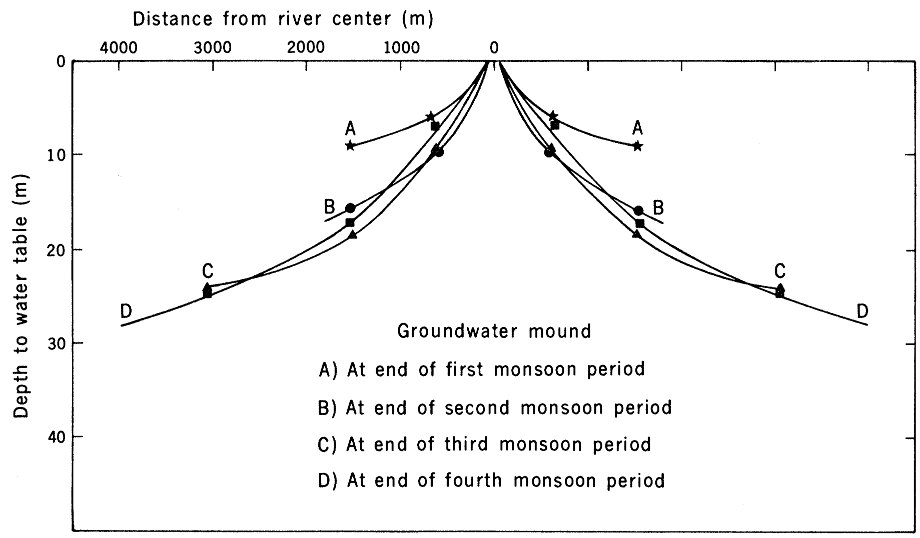

Fig. 2. Growth of groundwater mound under uniform recharge from river.

Advantages of Aquifer Storage

Flood amelioration. During the flood wave there will be much more bank storage than there is now along the tributaries where the water table has been lowered by pumping. This will supplement the aquifer storage described above in reducing downstream flooding. The amount of bank storage can be computed from the equations of Cooper and Rorabaugh (*8*).

Assuming a flood duration of 3 days, a flood crest of 3 m, aquifer transmissibility of 4650 m^2/day, and a storage coefficient of 0.25, the amount of bank storage 2 days after the beginning of the flood will be 2.3×10^5 m^3/km. This temporary bank storage is 50 percent of the water entering the aquifer during the same 2-day period; 75 percent of the bank storage will return to the river during the following 7 days.

Use of stored monsoon waters in irrigation. The area to be irrigated with the pumped waters would be larger than that of the well fields. Assuming 6×10^6 ha-m of storage from the monsoon flow, and adding the rainfall infiltration of 0.15 m, the gross irrigated area would be 17.5 to 19 m-ha. Here we assume that an amount of water equal to 10 percent of consumptive use by evapotranspiration is allowed for drainage to maintain a salt balance, or alternatively the original dry season flow of the river is returned downstream of the well fields in order to maintain the low flow. If the irrigated areas, including the zone of intense pumping, were located in strips along both sides of the rivers used in the scheme, the average width on each side of the rivers would be roughly 27 to 30 km.

Allowing for 20 percent return infiltration of the pumped water, the total pumping from the irrigated area during the dry season is about 10.5 $\times 10^6$ ha-m, requiring a total well capacity of around 5000 m^3/sec. If the well fields are 6 km wide on either side of the river, more than half the net volume pumped would need to be transported to the outer 21- to 24-km strip in surface conveyance channels. Since unlined channels inevitably leak into the ground a considerable fraction of the water they carry, this surface distribution system could, with proper management, also be used as a groundwater storage mechanism. For example, if the channels extended to the river, they could be used as inundation canals for irrigation during the monsoon season, and 30 to 50 percent of the water carried in them would be expected to seep downward to the aquifer.

Possible Tributaries for Monsoon Storage

Table 2 shows possible river reaches along which the underground storage scheme for the monsoon waters might be used, and Table 1 shows a possible future water budget for the Ganges Plain. It will be seen that in the western tributaries the initial dry-season flow would be about 25 percent of the water coming from the rivers into the aquifer. A portion of the pumped water would be needed for water supply and waste disposal for cities and towns along these rivers; return flows from irrigation could also be used for waste disposal. In either case, conveyance channels or pipes for the pumped water would be required. In the central and eastern plain, the dry-season flow probably comes largely from the Himalayas and equals 42 to 77 percent of the quantity of stored monsoon water. For economy in pumping and ease in maintaining the low flow water supplies for cities and towns, it would probably be desirable to construct diversion barrages upstream of the well fields and lined channels to carry the diverted water downstream of these fields.

Costs and Benefits of the Storage Scheme

Power requirements for pumping stored monsoon waters. Assuming an average pumping lift of 30 m, the net electrical energy required to pump 10.5 $\times 10^6$ ha-m would be 8.75×10^9 kilowatt-hours. With an overall efficiency of 67 percent, including transmission losses, the energy required at the generating plant would be 13×10^9 kwh, corresponding to an installed power capacity of 3000 megawatts at 50 percent load factor.

The electrical power requirement could be supplied by mine-mouth electric generating plants in the Raniganj-Jharia coal fields in Bihar, or by utilizing a small fraction (possibly less than 15 percent) of the enormous potential hydroelectric capacity of Nepal. (It is sometimes said that the force of gravity, expressed in falling water, is Nepal's principal natural resource.)

All the methods we have described for underground storage of monsoon waters would involve use of electric or diesel power for pumping. Because of the greater depth of pumping, the energy requirements for the river storage scheme would be larger than for other methods. But the ratio of benefits to costs would still be high.

Annual costs and benefits of the storage scheme. At $0.02 per kilowatt-hour, the annual power cost would be $260 million, or about $14.50 per gross irrigated hectare. At $0.005 per kilowatt-hour, the power cost would be $3.65 per gross irrigated hectare.

Construction costs of tube wells per unit of capacity diminish with increasing well capacity. Compared with larger wells, the maximum cost should be for wells pumping 0.03 m^3/sec. Assuming that the cost is $10,000 per well, the total cost for 170,000 wells would be $1.7 billion. Amortized over 10 years at 8 percent, the annual costs of well construction would be roughly $14.00 per gross irrigated hectare. To these fuel and capital costs should be added the cost of land for the tube wells and the drainage and conveyance channels, the cost of constructing these channels, and the labor costs for maintenance and operation of the system. With our present information we are unable to estimate these costs, but we believe they should be less than $15 per year per gross irrigated hectare.

The total annual costs would thus be about $40 to $45 per gross irrigated hectare. With adequate water management and proper use of fertilizers and other inputs, it would be possible to obtain high productivity from high-yielding crop varieties on the irrigated fields, in contrast to the present yields from traditional varieties, which must be used on unirrigated lands. The gross value of cereal crops would be of the order of $500 per hectare, ten times the annual costs of irrigation water supplies.

Of equal importance would be the increased food production from the newly irrigated lands. For the entire Ganges Plain, the storage of monsoon waters along tributaries by the pumping scheme we have proposed would provide a basis for an increase in production of 55×10^6 metric tons per year. All storage methods combined, together with increased kharif irrigation from canals, would give more than 110×10^6 tons above present production, enough by itself to provide a greatly improved diet for 400 million people.

In Table 1 we estimate that 6×10^6 ha-m would be used for irrigation during the kharif season of monsoon rainfall and high river flows. The necessity for irrigation in this season is due both to the large variation from year to year in total monsoon rainfall and to the intraseasonal irregularity of the rainfall. In many areas, water supplies for monsoon irrigation could be obtained by construction of barrages across Ganges tributaries, which will divert waters into systems of canals, distributaries, and water courses. From 35 to 50 percent of this water will seep into the ground and can be used for well irrigation during the dry season. Thus, the possibilities for total underground storage are much larger than our estimates of the storage that can be obtained by pumping out the aquifers along tributaries. The total potential irrigation in the Ganges Plain may be limited by the area of irrigable land rather than the water supply.

Need for Further Investigation

The choice between systems for storage of underground water will vary from region to region, and possibly with the stage of development of the integrated system of surface and groundwater irrigation. Further detailed field investigation and systematic analysis are required to determine the choice and sequence of investments for irrigation. Among the factors which should be considered are: the effects of sediment transportation and deposition, which might reduce infiltration rates from the rivers, the possible hazards of subsidence resulting from lowering the water table, and possible ecological effects. Special attention should be paid to design and construction of irrigation projects that are compatible with the long-range objectives of storing monsoon waters and maintaining the present volume of flow during the dry season. Projects that are incompatible with these objectives should not be initiated.

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9. The consumptive uses of irrigation water as of 1968–1969 are computed as follows: 4.15×10^6 ha are irrigated from storage reservoirs and canal systems, 1.55×10^6 ha from tanks and other minor surface storage, and 4.41×10^6 ha from wells. This gives a total net irrigated area of 10.1×10^6 ha. Assuming the depth of water consumed in field evapotranspiration and drainage is 45 cm, 20 percent of water diverted for irrigation from large reservoirs and canal systems is lost by evaporation, mainly in the reservoirs, and 90 percent is lost from tanks, then the total consumptive use is 3.6×10^6 ha-m for surface irrigation and 2.0×10^6 ha-m from wells. The allocation of irrigation waters between kharif and rabi seasons is our best estimate based on irrigation practices in the Ganges Plain. It is generally recognized that present irrigation supplies are inadequate. In considering modification of present systems and future irrigation, we have assumed that average field evapotranspiration and drainage will be 50 cm, including nonbeneficial uses. For 37.5×10^6 gross irrigated hectares, consumptive use plus other evaporation losses would be about 20.6×10^6 ha-m.

The average amount of water evaporating from the water table is probably between 2 and 3 cm. A reduction of 2 cm over an area of 40×10^6 ha might be obtained if the average depth to the water table were lowered by a few meters. This should not seriously interfere with the seepage of groundwaters into the rivers, which is the source of much of the river flows during the dry season. We estimate that construction of a sufficient number of low bunds at right angles to the flow lines in uncultivated areas might increase rainfall infiltration by 10 percent or 0.7×10^6 ha-m.

Dasheen leaf [*Courtesy U.S. Department of Agriculture, Washington, D.C.*] →