

A new solution for city water: quality drinking water from the river floodplains

Vikram Soni, Shashank Shekhar*, S. V. N. Rao, Suman Kumar and Diwan Singh

Cities world over are facing drinking water problem. The planners are often over emphasizing on sourcing surface water from far off places. This will involve exorbitant cost and many a times diversion of river flow beyond the permissible limit. Obviously such river flow diversions will have adverse ecological consequences. In this context, the article reinvents traditional knowledge with sound scientific rigour. It argues for ecologically sustainable local solutions for meeting drinking water need of cities from flood plain of rivers. A case of river Yamuna in Delhi has been discussed to highlight the potential of flood plain aquifer as a drinking water source.

Keywords: River floodplains, quality drinking water.

MANY parts of the world and India are poised for water jeopardy. For example, most parts of northwestern and peninsular India, northern China and California, USA are water-stressed^{1,2}. In many parts of India groundwater levels are down by about 20 m and rivers are overused and silted and cannot be exploited further. Silt and sewage-infested riverbeds can be the cause of natural catastrophes – a recent ones being the flood in Kashmir and Chennai.

Cities need to find a solution for sourcing water that is not injurious to the planet. For example, a dam is hugely invasive for the mountain ecology and the rivers, and needs a large-scale resettlement of the people. Tertiary recycling of wastewater, good for just kitchen use and not drinking, is expensive. In a city, there is no space for large reservoirs, which would anyway lose about 2 m of water every year by evaporation³. It is crucial to find a new source of water and use it non-invasively as a perennial resource.

The floodplains of the Himalayan river systems are extensive sandy aquifers that are 5–20 km wide and on an average about 100 m deep, and run for hundreds or even thousands of kilometres along the rivers⁴. The floodplains are a huge natural storage of quality water without any evaporation losses.

India receives 80% of its rainfall in about three months during monsoon⁵. This recharges the floodplains of the rivers on an annual basis. Here we show that for a large

number of cities by the rivers, an ecologically safe use of such rainfall recharge can provide a non-invasive solution for city water.

To be sustainable and perennial, it is crucial that we do not use any more water than is naturally recharged. In this study we examine in detail, the hydrology of floodplain aquifers of River Yamuna and work out the quantum of natural recharge in the northern part of its floodplain in Delhi. From this we work out an ecological process for a local, perennial and sustainable supply of quality water for Delhi, and other towns and cities located near the floodplains of a river.

Till now the floodplains have been used randomly without any detailed research and study. Often this has resulted in indiscriminate use, terminally polluting such aquifers. Hence, in this study we work out an ecologically safe process for sustainable water use from these aquifers.

Floodplain recharge

To begin with, we illustrate the water-holding capacity of the floodplain sand aquifer using a simple experiment^{1,6}. Suppose we take an equal amount of dry river sand and water in two identical glass tumblers and start pouring the water into the tumbler with sand. We find that about half the water glass can be emptied into the tumbler with sand (Figure 1). ‘Sand and gravel are great for water storage – they are aquifer material’¹.

Natural underground storage

The Yamuna river floodplain is about a 100 sq. km in area and on average 50 m deep and runs for a river length of about 50 km in the National Capitol Territory

Vikram Soni is in the Jamia Millia Islamia University, New Delhi 110 025, India and Jawaharlal Nehru University, New Delhi 110 067, India; Shashank Shekhar and Suman Kumar are in the Department of Geology, University of Delhi, Delhi 110 007, India; S. V. N. Rao is in the Water and Power Consultancy Services (WAPCOS), Hyderabad 500 004, India and Diwan Singh is in the Natural Heritage First, Vasant Vihar, New Delhi 110 057, India.

*For correspondence. (e-mail: shashankshekhar01@gmail.com)

(NCT)^{1,5,6}. Even after gravity compaction, it holds a lot of underground water – about 35–40% of this volume is water. Between 12% and 20% of the total volume of the aquifer can be withdrawn – this is called the specific yield. Can we use this?

The sandy aquifers in the floodplain get recharged during monsoon season by rainfall and consequent runoff from the catchment coupled with the flood water flow from the river. This annual recharge of water can be easily tapped from a grid of tube wells. It does not require construction of any structures such as dams/reservoirs. The high-yielding aquifers of the extensive floodplain can be used for drinking water supply to habitations near the floodplains. However, withdrawal of water from the floodplain is subject to a condition. For the preservation of this irreplaceable and evolutionary resource, it is of utmost importance that we pull out no more water than is naturally recharged by rainfall and floods. This is the only way to ensure the health of the floodplain as a perennial and self-sustaining source of water.

The Yamuna floodplain ‘conserve and use’ scheme of Palla region in Delhi

Floodplain potential and hydrology

One of the foremost assessments to be carried out before planning to utilize the floodplain is to make a hydrologic assessment of its potential. The aquifer properties like hydraulic conductivity, porosity, specific yield and specific retention are indicative of the amount of storage and potential supply from the aquifer. The river hydrographs and well hydrographs in and around the floodplain help in quantifying the amount of recharge. Pumping and recuperation tests help in understanding the aquifer response to pumping and recharge.

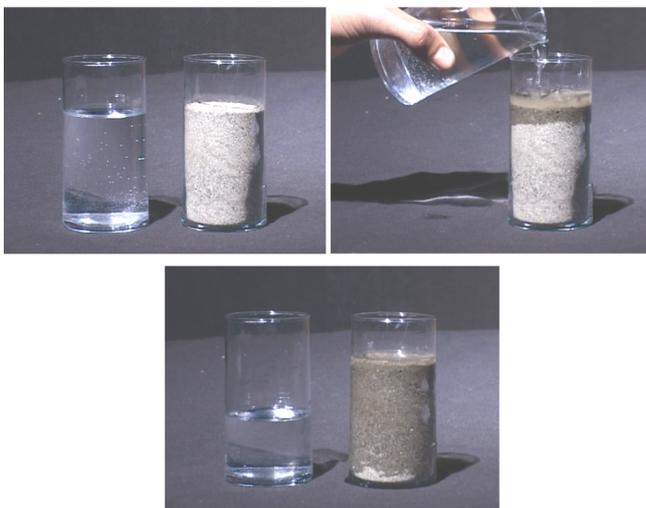


Figure 1. Water-holding capacity of sandy aquifers⁶.

The sandy layer of the floodplain of River Yamuna (within the embankment with yellow ochre line in Figure 2) around Delhi is on an average, about 50 m deep and extends to about 5 km width. The Yamuna floodplain receives about 60 cm of rainfall annually⁷, which is important for recharging the aquifers in the floodplain.

Exceptional aquifer

The younger alluvium of the floodplain aquifer is a well-connected system. It has high groundwater yielding and transmitting capability^{7,8}. Pumping tests involving drawdown, recuperation and aquifer performance are often conducted to determine aquifer parameters and safe yield. A similar stress test was conducted on these aquifers in the Palla area of Delhi (site shown as pumping well in Figure 2).

Stress tests

Pumping from this floodplain aquifer, at an average rate of 0.3 MGD (million gallons per day), produces a steady and stable flow of water. We found in that even sustained continuous pumping for 72 h did not diminish the output of water from this aquifer. This is completely distinct from other inland aquifers, whose yields decrease rapidly in a few hours. All these tests were carried out in the Yamuna floodplain using specially installed piezometers along with transducers to measure water level during the pumping tests for 48–72 h. Table 1 shows typical results of aquifer parameters arrived at using Aquifer Test Pro software. It indicates good aquifer properties for sustainable yield from the aquifer system. (It may be noted that there was no pumping from other wells in the vicinity when the tests were conducted.)

We obtained a deeper insight into the system using a long-duration pumping test data from a pumping well in the Palla well field (Figure 2). The well was pumped for 72 h at an average rate of 1.378 m³/min. Figure 3 is a plot of the representative water-level behaviour in the aquifer from an observation well (OW 2) at a distance of 30 m from the production well. The data were analysed using type-curve approach developed by Boulton⁹. Hydraulic conductivity was estimated¹⁰ as ~14 m/day and specific yield as 0.24.

We observed that such long-duration pumping for 4320 min led to drawdown of only 0.44 m in an observation well located at a distance of 30 m from the pumping well (OW2, Figure 3). After cessation of pumping, the aquifer recovery was fast and the locally dewatered aquifer during pumping was subsequently replenished by gravity groundwater flow. About 37% recovery was observed within 4 min after cessation of pumping. After initial recovery, the hydraulic gradient was found to

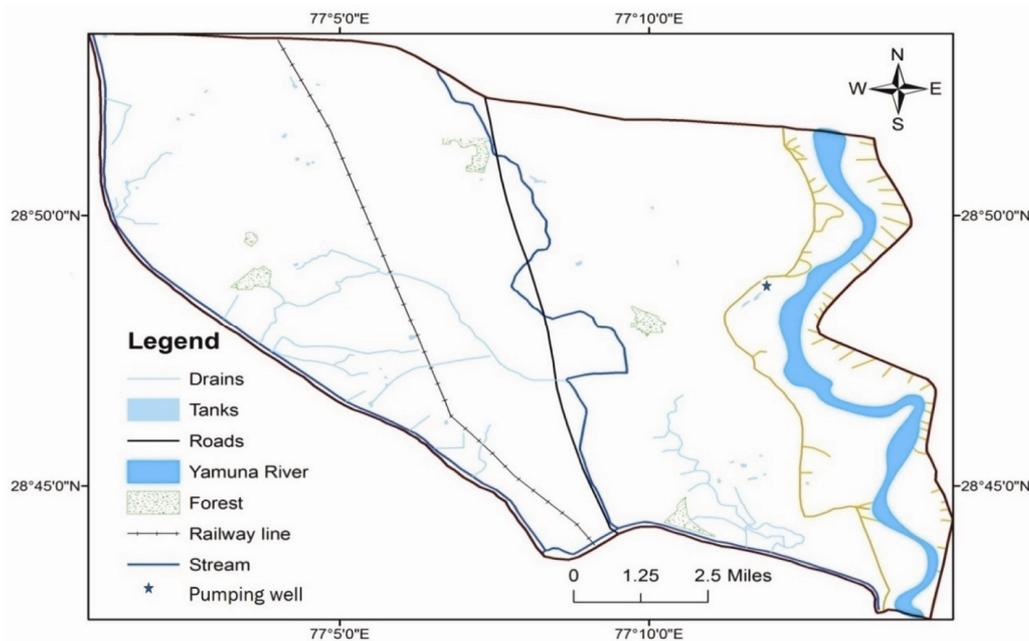


Figure 2. Floodplain of River Yamuna in North Delhi⁶, Yellow ochre line is the embankment.

Table 1. Experimental study report by WAPCOS for the Delhi Jal Board 2011

Site no	Well no.	Hydraulic conductivity (m/day)		Transmissivity (m ² /day)		Storage coefficient/specific yield	
		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
1	14/60	19.5	24.5	2150	2700	0.10	0.165
2	48/60	60	66.7	5400	6000	0.34	0.38
3	16/60	20.9	31.8	1150	1750	0.282	0.37

decrease and hence the velocity of flow. Nevertheless, we observed that after 8 h, residual drawdown in the observation well at 30 m was only about 0.19 m. This indicates that the continuous and extended aquifer of the floodplain is effectively recharging the aquifer. Any withdrawal will cause only a marginal decrease in the groundwater level.

Specific yield

For quantification of water yield, the specific yield of the aquifer is an important parameter. This is the maximum percentage of the aquifer volume that can be withdrawn as water. Because of compaction due to gravity, such an aquifer holds a quantity of water equivalent to about 40% of its total volume; this corresponds to porosity of the aquifer⁸. The average specific yield estimated during the study was around 0.3 (Table 1). However, other workers^{11,12} have reported specific yield of the younger alluvium in Delhi to be around 0.20, which is 20% of the aquifer volume. We have taken the lower value for further estimation as an assured minimum.

With this specific yield and assuming a floodplain width of 5 km and a depth of 50 m of young alluvium (sand), we found that a maximum of about 50 MCM of groundwater per kilometre of river course could be extracted. This volume is the maximum possible withdrawal that would leach the Yamuna floodplain aquifer – which is purely a theoretical construct for estimating the total drawdown capacity of the aquifer and, of course, practically insupportable. Here we show that only about one-tenth of this (5 MCM/year) is recharged and can be withdrawn sustainably.

Quality of water

The significant feature of the floodplain aquifers is that their water is of good quality, while the river water is polluted by sewage. The reason for this is that the recharge takes place by rainfall which is unpolluted and by flooding which occurs late in the monsoon (end August–September) which is also unpolluted water, as pollution has been flushed out in the earlier phase of the monsoon.

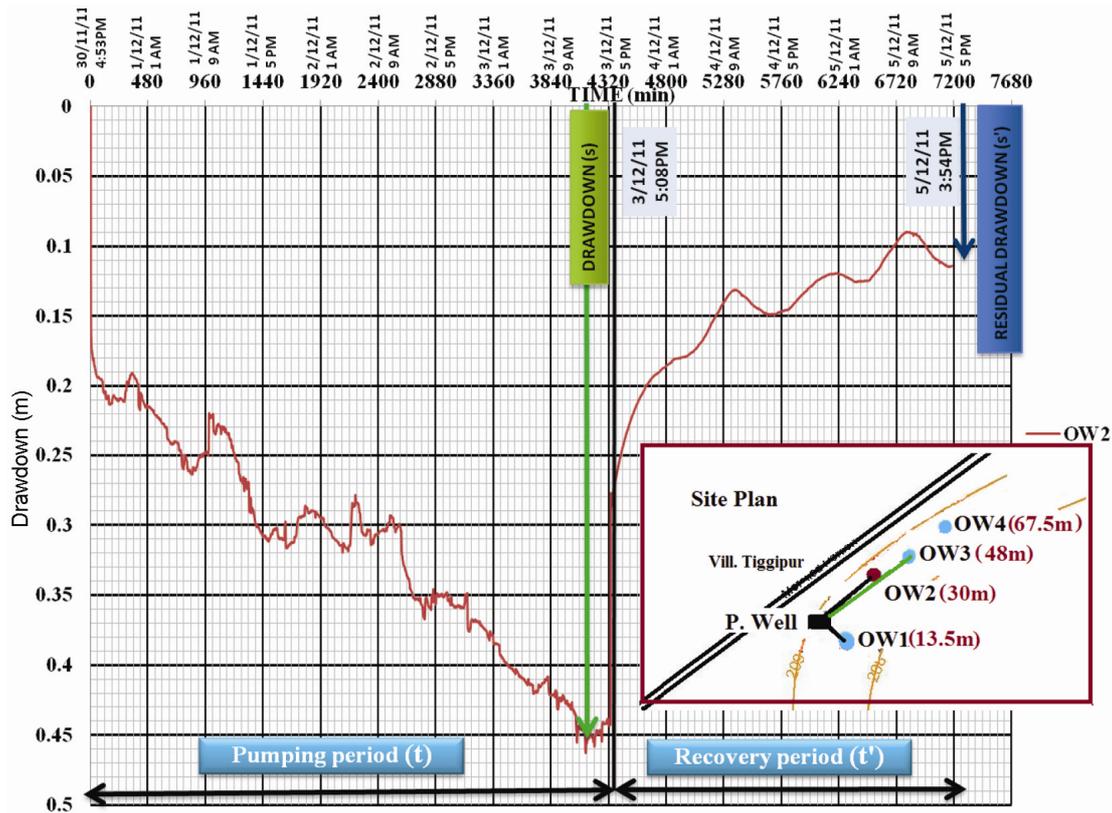


Figure 3. Plot of drawdown and recovery during long duration test¹⁰. (Inset) Position of observation wells (OW 1 to OW 4) with respect to pumping well (P. Well).

Table 2. Analysis of groundwater samples at different depths for commonly found contaminants

Location ID of well	Observation well depth (m)	Concentration (mg/l)					EC value (µs/cm)
		Iron	Fluoride	Manganese	Nitrate	Ammonia	
		Permissible limits (mg/l)					
		1.0	1.5	0.3	45	0.5	
48/60	10	0.06	0.27	0.06	0	0	500
	20	0.08	0.6	0.06	0	0	550
	30	0.2	0.24	0.14	0	0	260
	60	0.08	0.21	0.26	0	0	280
41/60	10	0.11	0	0	0	0	450
	20	0.73	0.5	0.21	0	0	640
	30	0.25	0.68	0.22	0	0	380
	60	0.23	1.58	0	0	0	330
16/60	10	0.28	1.3	0.17	0	0	630
	20	0.2	1.06	0.33	0	0	680
	30	3	0	0.26	1.05	0.11	950
	60	0.44	0	0	0.54	0	680
14/60	30	0.11	0.21	0.33	1.38	0.11	900
	60	0.44	1.3	0.39	1.05	0	1050

Source: Report by WAPCOS for the Delhi Jal Board, 2011.

The quality of floodplain water is far better than the polluted river water. This is due to the fact that in the lean season it is the floodplain which feeds the polluted river and not the other way. River water does not travel more than 200 m laterally in the floodplain⁵.

Analysis of groundwater samples for commonly found contaminants in the floodplain (Table 2) reveals that the groundwater is well within health safety limits. *Escherichia coli* was found to be absent in all groundwater samples.

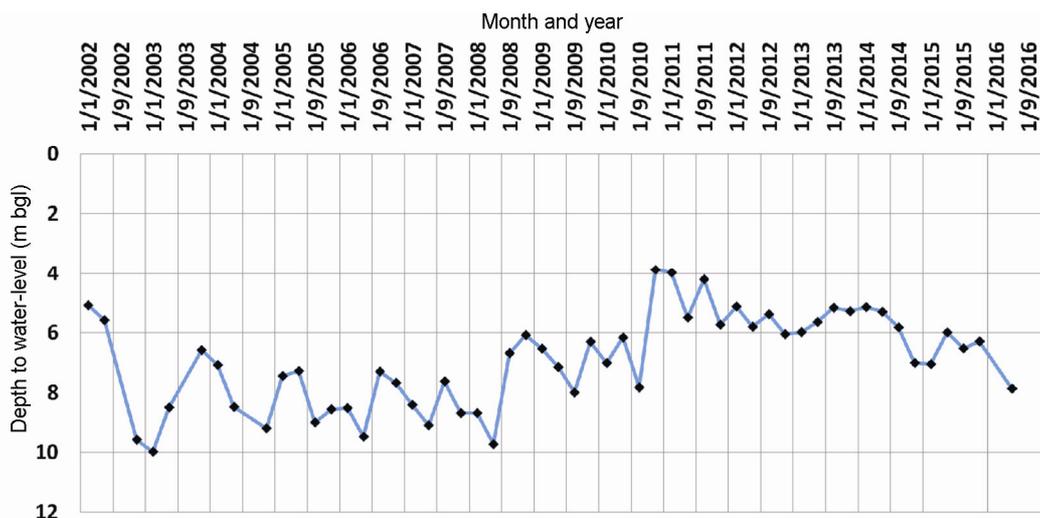


Figure 4. Groundwater level of hydrograph at Palla temple site, Yamuna floodplain, Delhi (source: CGWB data).

Four representative pumping wells were chosen and data was collected from 14 observation wells around the pumping wells in July 2013 (Table 2).

Extensive self-sustaining aquifers

Even when there is no recharge from rainfall, a study of the floodplain hydrographs reveals that for an area where water is withdrawn locally, the rest of the surrounding floodplain rapidly recharges the area by gravity flow. Thus the groundwater levels in the floodplain diminish only marginally after withdrawal. The study shows that whereas withdrawal of water for the other aquifers without the surrounding recharge would reduce groundwater level by about 9 m; in the case of the floodplain, which is an extensive and exceptional aquifer, the groundwater level comes down by only 2 m.

Groundwater-level hydrograph for the Palla aquifer

A yield of 45 MCM/year (30 MGD) over an area 25 sq. km, from the Palla wells translates to a withdrawal of about 1.8 m of raw water/year (ref. 13). At a specific yield of 0.2 (20%), the groundwater level would diminish by five times the raw water withdrawal or by about 9 m, under conditions of zero recharge. Actual data show an average fall in groundwater level by 2–3 m followed by recovery post-monsoon (Figure 4).

Groundwater-level hydrographs for other locations

1. The Akshardham Yamuna floodplain shows a fairly steady average groundwater level with some rising trend. Actual data show seasonal fluctuation in groundwater level 1–2 m with good recovery post-monsoon (Figure 5).

2. Figure 6 shows a typical well hydrograph in the eastern Yamuna floodplain of Mayur Vihar, adjacent to Noida, Uttar Pradesh. The hydrograph shows stability and rise in water level after 2010, in spite of the fact that in Noida abstractions from 182 tube wells and 6 Ranney wells are about 85 MCM for a population of about one million (personal communication, sourced by V.S.). Actual data show an average fall in groundwater level by ~1–2 m followed by recovery post-monsoon.

This establishes the fact that for this extensive aquifer, rainfall and flood recharge replenish it on a sustainable basis.

The site-specific rainfall monitoring stations are not present at Akshardham, Mayur Vihar and Palla. The average rainfall variation for New Delhi does not show a linear relationship with the water-level fluctuation (Figure 7; see also Figures 4–6). However, high monsoon rainfall after a series of low rainfall years immediately replenished the aquifer and may show a direct linear relationship between water level change and rainfall. However, the water-level fluctuations in subsequent high rainfall years were not sensitive to rainfall fluctuations (Figure 7; see also Figures 4–6).

Figures 8 and 9 show a water-level elevation maps of northern Yamuna floodplain of Delhi and indicate a maximum variation of 2 m between pre- and post-monsoon levels.

Quantification of recharge

Recharge

Withdrawal of water can only be viable and sustainable if the aquifer water gets replenished each year, thus placing ecological limits upon this process. We found that sustainable withdrawal for the Yamuna floodplain (on an

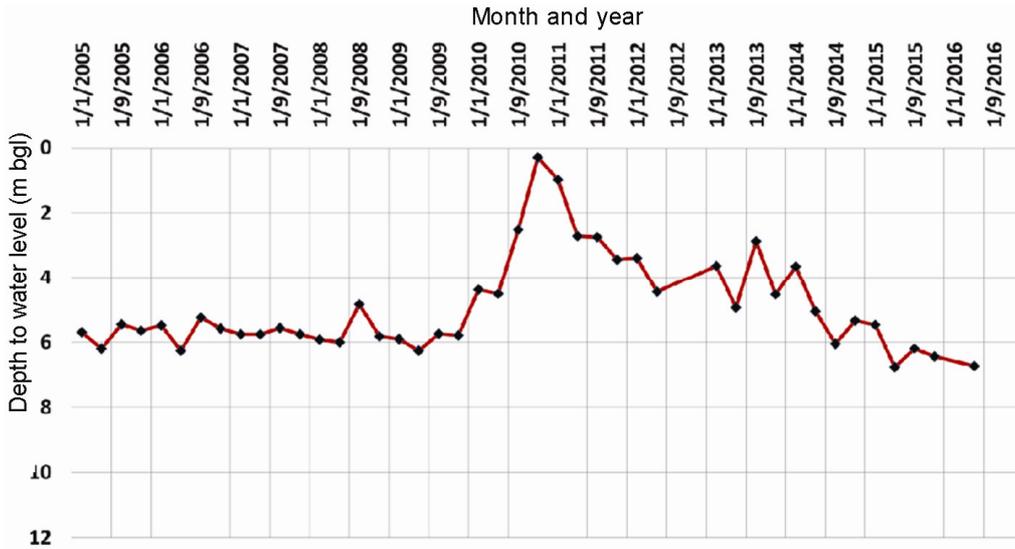


Figure 5. Groundwater level of hydrograph at Akshardham temple site, Yamuna floodplain, Delhi (Source: CGWB data).

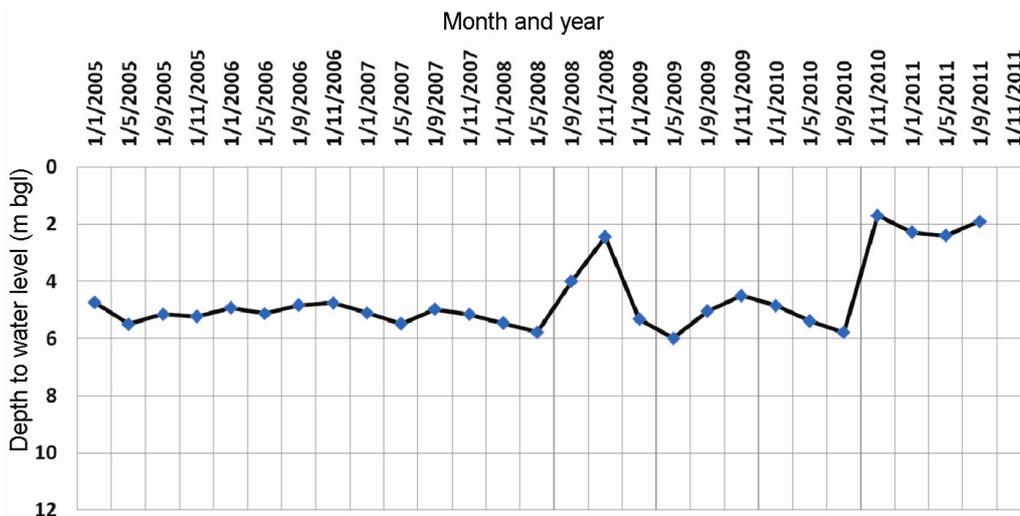


Figure 6. Groundwater level of hydrograph at Mayur Vihar site, Yamuna floodplain, Delhi (source: CGWB data).

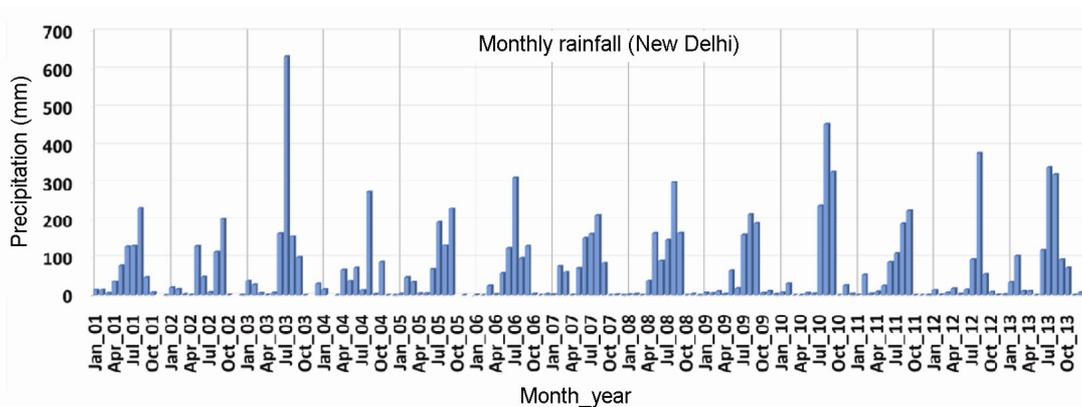


Figure 7. Monthly average rainfall in New Delhi.

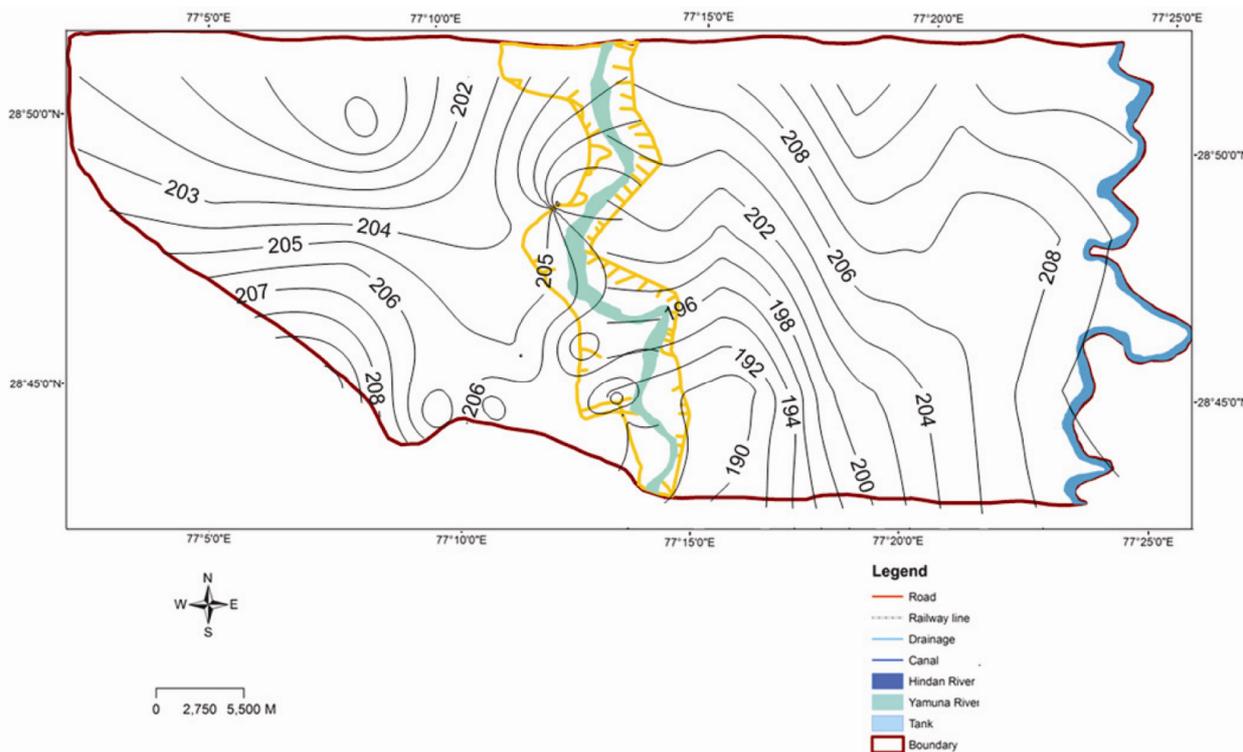


Figure 8. Water level elevation map of the northern part of Yamuna floodplain in Delhi for pre-monsoon of 2011 (ref. 6).

average about 50 m deep and about 5 km wide) which receives about 60 cm of rain annually, amounts to about 2% of the total aquifer volume. For the Palla floodplain it shows that for a river length of 20 km, we can expect about 100 MCM of annual sustainable withdrawal. Here are the estimates.

I. Simple estimation: Further recharge assessment in simplistic terms could be assessed arithmetically, by multiplying average fluctuation in water level spatially with area and specific yield (Figures 8 and 9). More detailed assessment needs to be carried out through groundwater modelling and verifying the well hydrographs under steady/transient conditions using historical data, aquifer parameters, lithology, recharge assessment and suitable boundary conditions. From the typical groundwater contours for pre-monsoon (Figure 8) and post-monsoon (Figure 9), we can get the following estimates for the Palla floodplain:

- (1) Area of influence zone, $A_{IZ} = 250$ sq. km.
- (2) Area of floodplain within embankments, $A_{FP} = 25-40$ sq. km.
- (3) Average specific yield within floodplain, $SY_{FP} = 0.2$.
- (4) Specific yield in adjacent areas, $SY_A = 0.15$.
- (5) Average hydraulic conductivity in floodplain = 30 m/day.
- (6) Average hydraulic conductivity in adjacent areas = 25 m/day.

(7) Rainfall recharge assuming average groundwater fluctuation (GF) of 2 m = $A_{IZ} \times GF \times SY_A = 250 \times 2 \times 0.15 = 75$ MCM.

However, we must always keep in mind that here the area of influence (250 sq. km) is a function of the rate of groundwater abstraction. If the rate of groundwater abstraction increases, the groundwater level decreases locally. It is then clear that the area of influence will also expand or increase as the surrounding flow contour can attract flows from areas that were previously below the local groundwater level, but are now above it. This implies that the recharge will also increase. However, there will be a threshold here, beyond which further abstraction of water will disturb the floodplain ecology.

The annual rainfall recharge of about 50% of annual rainfall (60 cm), i.e. 30 cm, in the porous and absorbent sand of the floodplain of about 250 sq. km gives ~75 MCM of recharge which agrees well with the above estimate.

- (8) Recharge from flooding within embankment with an allowed groundwater floodplain fluctuation (FF) ~ 4 m, (floodplain fully saturated) = $A_{FP} \times FF \times SY_{FP} = 30 \times 4 \times 0.2 = 24$ MCM.
- (9) Total recharge = 99 MCM.

II. Empirical verification from the Noida scheme: Noida is a large residential colony (203 sq. km) on the

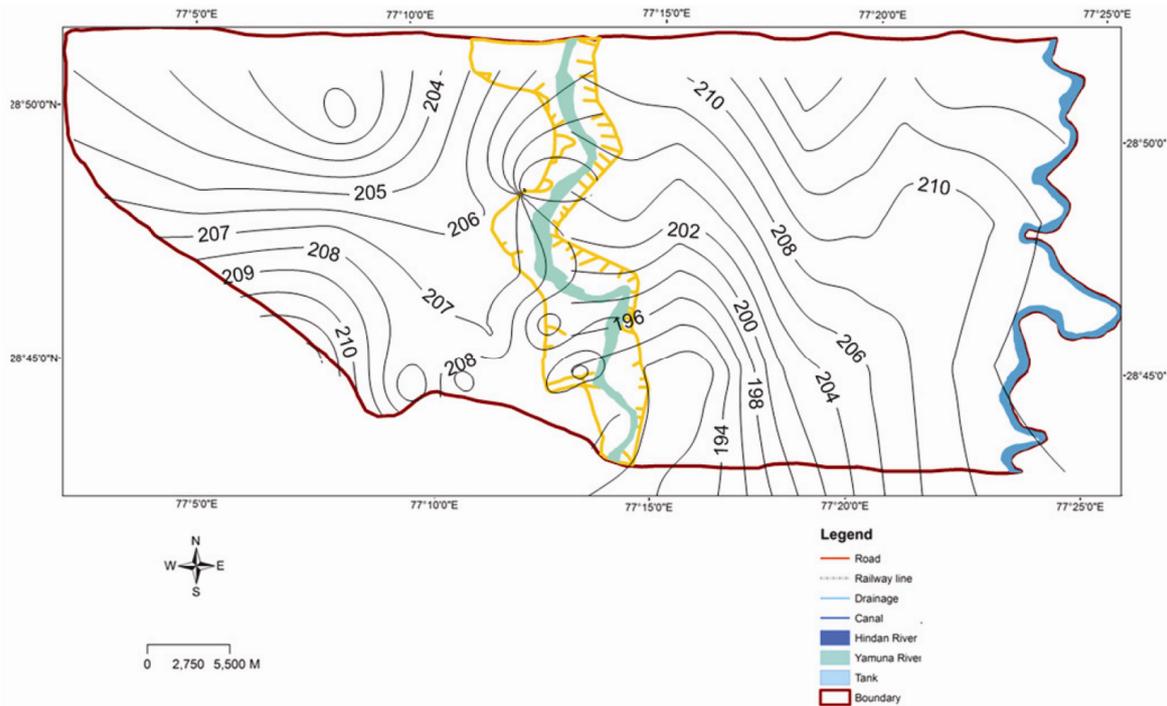


Figure 9. Water-level elevation map of the northern part of Yamuna floodplain in Delhi for post-monsoon of 2011 (ref. 6).

Yamuna floodplains. It has a population of about 1 million, an industrial estate and development activity with a large informal migrant population. It receives water supply 200 MLD from the floodplain through 182 tube-wells and six Ranney collector wells, which works out to 85 MCM/year. Pumping has been implemented in an arbitrary manner without any comprehensive hydrological study.

The wells are located here in about 25 km stretch of the flood plain along the river course. Since the Noida floodplain-based water supply has been in place for over 20 years with only natural recharge, it is empirically established that the natural recharge estimated by us is valid.

However, recently, Noida is sourcing its water from the Ganga River, as this floodplain aquifer has been over-exploited and has become polluted by industrial waste via Hindon River and sewage from the Yamuna. Further, uncontrolled sand mining along the river bank which can bring the floodplain surface below lean season river-water levels, allows pollution to percolate into the aquifer.

III. Computer simulation of recharge (An example from Palla well field in Yamuna flood plain of Delhi): Recharge assessment and impact of pumping stresses can be verified with reasonable approximations using computer simulation based on aquifer properties, boundary conditions and historical well-water level hydrographs. Recharge is estimated from rainfall recharge data, monsoon

flooding, and downstream and lateral groundwater mobility in the floodplain.

Broadly the objectives of the modelling study include:

- Determine the response to existing pumping/recharge on groundwater regime.
- Quantification of ecologically safe water yield from the floodplain on a sustainable basis, both in terms of quality and quantity.
- Design of a Supervisory Control and Data Acquisition (SCADA) system for optimal well-field operations.

Mathematical modelling to verify well hydrographs or aquifer response to stresses could be done by solving numerically the conservation equation in the partial differential using a finite difference approach given below.

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) + W = S_s \frac{\partial h}{\partial t}, \quad (1)$$

where K_{xx} , K_{yy} and K_{zz} are values of hydraulic conductivity along the x , y and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T); h the potentiometric head (L); W the volumetric flux per unit volume representing sources and/or sinks of water, with $W < 0.0$ for flow out of the groundwater system and $W > 0.0$ for flow in ($L^3 T^{-1}$); S_s

the specific storage of the porous material (L^{-1}) and T is the time (T).

For example, computer simulation based on estimated aquifer parameters, at the current operational discharge of 35 MGD in Palla area, yields the well hydrograph given in Figure 10. This shows a post-monsoon fluctuation in the range of 1.5 m.

The simulated hydrograph shows only a 1.5 m drop in groundwater level. As we have remarked before, if we increase the discharge, the area of influence also increases, and thus there is only a small and ecologically safe drop in groundwater level. Modelling studies show that the natural recharge by rainfall and floods and downstream movement of water in the floodplain during monsoon can sustainably yield about 60 MGD (100 MCM) of water per year for the entire Palla floodplain.

Design of a perennial, sustainable, non-invasive process for annual supply from floodplain aquifer

Design of well grid on the floodplain: Depending on the hydrology of the river, specific yield, aquifer stratigraphy, geo-physical investigation, groundwater modelling for optimal well locations and experimental tests, we can place tube wells/Ranney collector wells at an interval of 0.5–1 km in the floodplain, as illustrated in (Figure 11).

Furthermore, pumping needs to be regulated (in terms of quality and quantity) in space and time on a real-time basis. For this, we employ the SCADA system that will ensure parameter values to be regulated through sensors. The monitored parameters include discharge, pressure, salinity (and fluorides, nitrates, etc.), groundwater level, power factor, power consumption, etc. for each well and will be guided by pumping patterns in space and time. This is accomplished with the help of sensors installed in each tube well. Importantly, the groundwater level should not fall below a desired value to ensure that the submersible pump is safely under groundwater level for uninterrupted pumping. Secondly, salinity is measured in terms of electrical conductivity (EC) to ensure that only freshwater of desired quality is obtained. Optimal pumping patterns could be generated for different scenarios for the management of the aquifer.

Economic value

It is easy to estimate economic value for this water¹. The recharge yield of the northern half (Palla) of the Delhi Yamuna floodplain is about 60 MGD (100 MCM/year). At the highest slab of the commercial tariff charged by the Delhi Jal Board (DJB) at present, which is ~Rs 160/m³ (djb.gov.in), the market value of this water works out to over Rs 1500 crores a year¹. Even if we value the water at the subsidized rates of the DJB for

domestic consumers (Rs 46/m³) it would still work out to about Rs 500 crores a year.

This scheme is already running and providing 30 MGD (45 MCM) from the Delhi Palla floodplain (http://delhi.gov.in/Palla_Floodplain). This is the maximum water output that can be handled by the present pipeline. A new pipeline is due to be laid, which will increase the water output to 60 MGD.

We would like to state that recycling the same volume of water for drinking works out to be much more expensive.

Cost

This scheme is perennial and sustainable while being low-cost – an annual yield of 100 MCM would cost about Rs 100 crores for installation of borewells, a pipeline and SCADA system which will have sensors for all quality parameters and computerized operations for optimal pumping. The operation and maintenance costs would be less than Rs 10 crores a year – compare this with the yearly economic benefit.

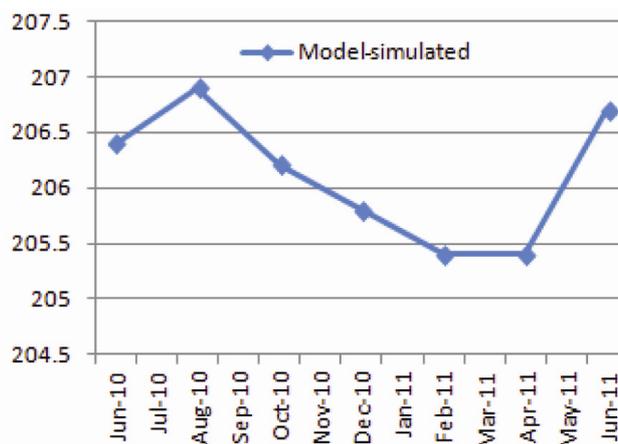


Figure 10. Groundwater model-simulated hydrograph at a site in Palla area of Yamuna floodplain, Delhi.

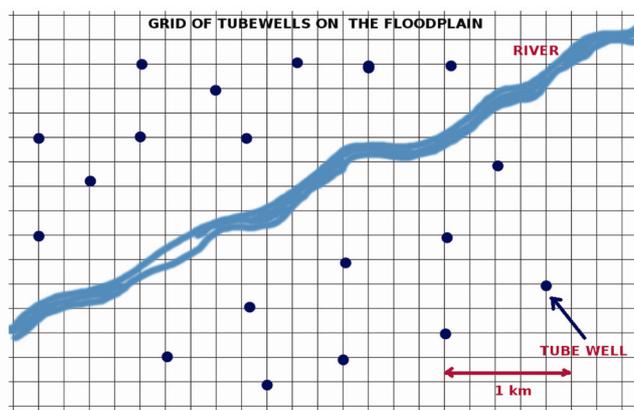


Figure 11. Optimal location with respect to grid in the floodplain.

Conclusion

As we have indicated, this 'conserve and use' scheme is already working on the Yamuna floodplain in Delhi, and apart from providing sustainable water for about a million people, it is a revenue windfall for DJB. It may be replicated in a number of riverside cities.

Recycling water at a huge cost with advanced technology will dispense more waste in the environment; it is rather economical to have an ecologically sustainable perennial source of water virtually free of cost. Such novel schemes can provide drinking water to cities which have rivers flowing through them. There are numerous river side cities in India with a population less than three million in which all the drinking water needs can be met by the floodplains. In Bhubaneswar, Odisha, rainfall is almost three times that of Delhi, i.e. 160 cm/year (ref. 1). The city can meet its drinking water needs from the extensive floodplain of the Mahanadi river, which flows nearby. Likewise, in other water-stressed parts of the world, like North China and the Middle East, this would be a boon for the people.

This non-invasive scheme works on natural recharge of water in the natural storage space available in the floodplains of rivers. It will serve as a drinking water source for hundreds of cities near the rivers. It is indeed a non-invasive, long-term solution to the drinking water woes of cities. Besides, this 'conserve and use' scheme provides a sustainable and perennial water solution which conserves the ecological integrity of the water resource. It also establishes the fact that the floodplains of rivers need to be preserved as a perennial source of quality drinking water.

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ACKNOWLEDGEMENTS. V.S. thanks Kapil Mishra (Minister for Water and Tourism, Government of India) for his interest in this project and the Delhi Jal Board (DJB) for collaboration. S.S. and S.V.N.R. thank DJB for providing funds to WAPCOS Ltd, Hyderabad for undertaking this study in the floodplain. A part of this study has been used in compiling an in-house project report of WAPCOS Ltd. A simple summary of the river hydrology and the floodplain scheme and groundwater issues has been incorporated by V.S. in his book¹.

Received 16 January 2016; revised accepted 24 August 2017

doi: 10.18520/cs/v114/i03/452-461