Environmental flow for the Yamuna river in Delhi as an example of monsoon rivers in India

Vikram Soni[1,*,†], Shashank Shekhar[2,*,†] and Diwan Singh[3]

[1]Jamia Millia Islamia University, New Delhi 110 025, India
[2]Department of Geology, University of Delhi, Delhi 110 007, India
[3]Natural Heritage First, B49A, Vasant Vihar, New Delhi 110 057, India

With an eye on all the natural functions of a river, the present article considers the flow of the river Yamuna in Delhi as an example of monsoon rivers in India. About 80% of the total virgin flow of Indian rivers is during the monsoon period and the remaining 20% is during the non-monsoon period. In case of the river Yamuna in Delhi, we find that at least 50% of the virgin monsoon (July to September) flow is required for transport of the full spectrum of soil particles in the river sediment. A similar flow is needed for adequate recharge of the floodplain aquifers along the river. For the non-monsoon period (October to June), at least 60% of the virgin flow is necessary to avoid growth of still-water algae and to support river biodiversity. We conclude that about 50–60% of the virgin flow is necessary throughout the year to maintain the health of the river system.

Keywords: Algal choking, environmental flow, flushing flow, monsoon rivers, sediment transport, soil particles.

A river, its catchment, basin and floodplain form a water course made by nature over an evolutionary timescale of tens of millions of years, which once damaged, often, cannot be fully reclaimed. Rivers in India are now overdrawn, silted and polluted. The health of the river system, then, becomes a priority.

Indian rivers are monsoon rivers which have deep and wide floodplain aquifers that run for thousands of kilometres and serve as an enormous natural storage for water[1,2]. They get recharged by the river flow and floods, especially during the monsoon period. They feed groundwater aquifers in their environs. Given the increasing scarcity of water, the rivers are likely to be one of few perennial water resources of the future.

If not polluted by human intervention, the water in a river is the best water. In the millions of years of flow the river has washed down salinity and other contaminants to give good quality 'mineral water', which makes the river a special and vital survival resource. Priority must rest in the sustainability of all the ecological services the river provides. Care has to be taken to avoid injury to the catchments, floodplains and the basin by overbuilding dams, canals and from the discharge of pollutants into the rivers. For this, environmental flow is required to maintain ecological integrity of a river as a perennial resource.

*For correspondence. (e-mail: vsoni.physics@gmail.com; shashankshekhar01@gmail.com)
†Equal contributors.

Preserve and use

In the present circumstances of water scarcity due to rising population, agriculture demands and urbanization, the question that is assuming immense importance is how to use river water resource in a non-invasive way? What is the maximum sustainable water use from a river that will maintain the ecological integrity of a river as a perennial resource?

Like any other living system, the river needs to cleanse itself. This happens when heavy rain helps the river to flush out pollutants, silt and the still-water algae. For Indian rivers this happens during the monsoon, when 80% of all rain falls each year. It is during these periods of heavy rainfall that the river performs many essential functions. The much higher discharge during the monsoon markedly increases the velocity and depth of flow. This is essential for soil transport to avoid siltation of the riverbed – a dire need for our rivers today. The rise in the level of the river makes its reach and breadth larger. Flooding inundates the floodplains and large tracts of surrounding land recharging the groundwater. The faster flow also increases the water pressure on the sides, which is again good for recharge of the environs. Some of this flow is returned to the river by the floodplains during the lean season. This wetting of the surrounding areas also revives the good bacteria in the subsoil, which clean up the river. At the mouth or delta, the river performs the important function of stopping the saline ingress of the sea, supporting the barrier mangrove ecosystems and producing a fertile interface between the river and the sea both in terms of soil and fish – on which depend the livelihood of millions. We have to look upon the large monsoon flow as essential. If we cut this flow drastically, many of nature's functions and bounties that we take for granted will be disrupted.

A report by the International Water Management Institute[3] indicates that if a river is to be maintained close to its pristine state, approximately 60–80% of its total mean annual flow is required. The actual water use to avoid environmental stress should be not more than 50% of the total annual flow of the river (figure 2 in ref. 3).

Present river flows: Yamuna

The first question that arises is regarding the data on river and its flow characteristics. We carry out this exercise for the river Yamuna in the Delhi stretch (Figure 1). The problem here is that there are many sets of data available on flows and discharges, but they do not tally.

These flows must be consistent with such river parameters as the depth of the river channel during monsoon and non-monsoon periods, width of the river channel and velocity of the flow. These parameters vary along the river course; so we can only give averages. This determines the velocity of the flow – obviously the flow must be faster when the channel is narrower. When the flow is faster, the river transports more sand and other particulate matter from the riverbed.

At the outset we would like to point out that the subject of river flow is not an ‘exact’ or reductionist science like space science or nanoscience. It has to be holistic and convergent and thus sensibly approximate. Besides, we have to factor in that rivers are heavily used for agriculture, domestic supply in cities and for industrial supply, therefore, we cannot always demand pristine river flows. We have to safeguard all the essential natural functions of the river and yet be practical. Below, we shall use average parameters to find a consistent picture of the river dynamics for the case of the Yamuna river in Delhi.

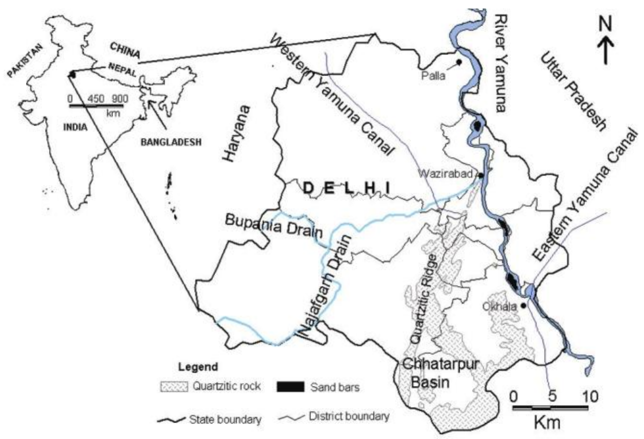

Figure 1. Location map of river Yamuna.

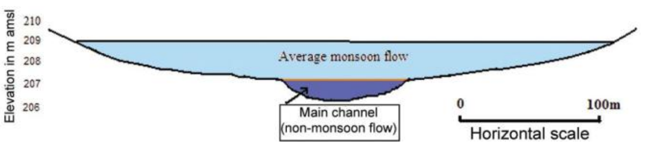

Figure 2. A generalized river cross-section from Palla area, north of Wazirabad (see Figure 1).

River flow analysis

The total mean annual flow for the Yamuna river up to the Delhi stretch (Figure 1) is about 13.9 thousand million cubic meter (TMCM)[4]. The water abstraction from river Yamuna for irrigation and drinking water uses till Delhi is about 9.5 TMCM (ref. 5). This leaves only a free river flow of about 4.4 TMCM. For the Yamuna, as for most Indian rivers, ~ 80% of the flow (~ 11 TMCM) occurs in the monsoon months (July to September) and 20% (2.8 TMCM) in the nine non-monsoon months (January to June and October to December)[4,5].

Data from the Irrigation and Flood department on monthly release of water from the Wazirabad barrage (Figure 1) in Delhi, indicate total release of 3.8 TMCM in the monsoon months and 0.3 TMCM in the 9 non-monsoon months[6].

Our estimate of the river flow in Palla region, Delhi is based on the following average set of data:

(i) The river cross-section which includes: (a) the main channel of the river (measured several times at many stretches) and averages about 80 m in width, which is occupied through the year, in particular during the non-monsoon period; (b) the gently sloping shoulder area outside the main channel, which is occupied by water when the river stage increases beyond 207 m amsl (Figure 2).

(ii) The depth of flow of water above the riverbed in the main channel averages to about 0.6 m during the non-monsoon period and rises to an average 2.5 m during the monsoon period. We assume a rectangular cross-section of the main channel: (a) of width 80 m and depth of flow of water of 0.6 m during the non-monsoon period; (b) of width 80 m and depth of flow of water of 2.5 m during the monsoon period.

(iii) During monsoon period the gently sloping shoulders have an average water depth of 1.9 m at the main channel, which goes to zero depth at the outer margins. Thus for monsoon flow through shoulder areas adjacent to the main river channel, we can approximate this by a rectangular cross-section of the mean average water column depth ~ 1 m and a width of 125 m on each side of the main river channel.

(iv) The measured average velocity of the flow during the non-monsoon period is ~ 0.4 m/s.

(v) The average slope of water surface is 0.00041.

From these data we determine the hydraulic radius of the flow. Using appropriate roughness coefficients which decrease proportionately with increase in river stage (see for example ref. 7 and Supplementary Information, online) for the flows in the main channel and shoulder during the monsoon and non-monsoon periods, we determine the velocities using Manning’s formula for different stages and width sections and the corresponding discharge. The data was used to prepare a scatter plot of total river discharge (including shoulder flow adjacent to the main river) versus river stage and an appropriate trend line was fitted in the plot. Thus a standard rating curve giving a site specific stage discharge relationship was prepared (Figure 3). A plot of river stage versus main river channel flow velocity for high stage flood including peak flow (Figure 4) was prepared to have an insight into relationship between river stage and main river channel flow velocity.

In the non-monsoon period, the average river stage of 207 m amsl corresponds to a river channel discharge of 19 cubic m/sec (Figure 3). As mentioned above, the average monsoon river stage is 1.9 m above the non-monsoon river stage of 207 m amsl; hence the average monsoon river stage in the river channel was estimated as 208.9 m amsl. This corresponds to the main channel river flow velocity of ~ 1.6 m/s in the monsoon period (Figure 4) and total river discharge of 507 cubic m/sec (Figure 3; see Supplementary Information, online, for details). We find good correspondence between our calculated discharge and the observed discharge.

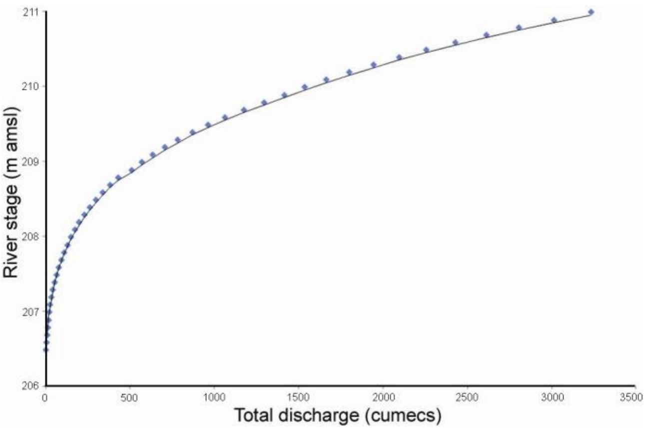

Figure 3. The stage–discharge rating curve for the site near Palla, upstream of Wazirabad (see Figure 1) in the Delhi stretch of river Yamuna.

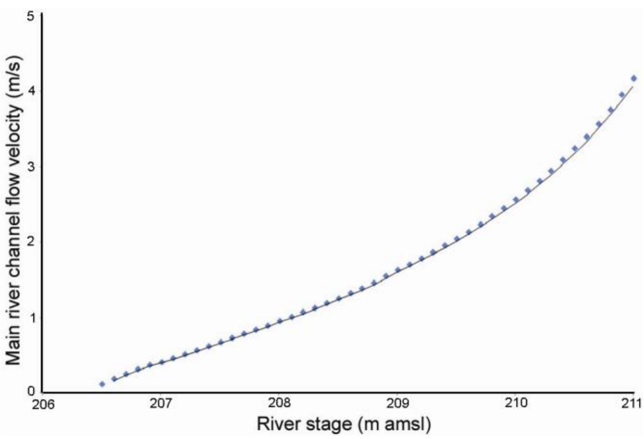

Figure 4. A plot of river stage versus main river channel flow velocity.

Non-monsoon flow

The total present non-monsoon flow in nine months was estimated at 0.44 TMCM (see Supplementary Information, online). As mentioned above, the total mean annual virgin flow of river Yamuna is 13.9 TMCM and 20% of this, i.e. 2.8 TMCM, is the non-monsoon virgin flow in the Delhi stretch (Figure 1). The present total non-monsoon flow in nine months calculated above as 0.44 TMCM is only 16% of the non-monsoon virgin flow of river Yamuna. This is not the ideal non-monsoon flow required for a river to perform its various functions.

Monsoon flow

The river flow regime widens considerably in the monsoon months. The flow regime can be segregated into river flow through the main river channel and through areas adjacent to the main river channel (Figure 2). The total monsoon flow in the main river channel in three months was estimated as 2.5 TMCM and in the shoulder areas adjacent to the main channel of river Yamuna it was approximately 1.5 TMCM (Table 1 and Supplementary Information, online).

Thus the present actual monsoon flow of river Yamuna upstream of Wazirabad barrage (Figure 1) has been estimated as approximately 4 TMCM, which gives an average monthly flow during monsoon months of approximately 1.3 TMCM/month.

A summary of river flow during different seasons is given in Table 1. It is estimated that the present mean annual flow through this stretch of river Yamuna is 4.44 TMCM. It is approximately 32% of the total mean annual virgin flow of river Yamuna through this stretch. It is to be noted that these discharge figures are average values and they are subject to annual variations.

Multiple environmental flow requirements

Environmental flow has multiple components, each pertaining to a particular natural function of the river for maintaining its ecological integrity. The question of what constitutes a flushing flow and its significance is a grey zone with varied opinions. Himalayan rivers carry enormous sand, gravel and silt load during monsoon. But the increasing diversion of water does not allow for natural flooding. Earlier, flooding used to deposit sand in the floodplains and carry the rest to the sea. But now, much of the soil is retained in the riverbed.

Thus, one important function of a Himalayan river in the monsoon period is to be able flush out this debris to avoid silting of the channel. This can only happen if the force or velocity of the flow is large enough to transport this material all the way to its mouth or delta. This has not been happening in most of the rivers where siltation

Table 1. A summary of river flow during different seasons

Season	River flow (TMCM) main channel	Shoulder flow	Total	Average river stage (m amsl)
Total monsoon (three months)	2.5	1.5	4.0	208.9
Total non-monsoon (nine months)	0.44	0	0.44	207
Total	2.94	1.5	4.44	–

of the riverbed is endemic and has recently also caused unnecessary flooding. Add to this the heavy sewage discharge of grit and even metallic waste into the river. It thus requires a strong flow to carry away these deposits and keep the purity of the river channel. There is a hierarchy of flows required for a river to perform its several natural functions. These are discussed below.

Algal choking

To avoid still-water algal growth we need a minimum flow velocity[8] of 0.75 m/s. The non-monsoon flow (nine months) of river Yamuna to do this is estimated to be 1.8 TMCM (see Supplementary Information, online), whereas the present total non-monsoon flow is just 0.44 TMCM. The estimated desired minimum non-monsoon flow is approximately 60% of the estimated non-monsoon virgin flow of 2.8 TMCM in river Yamuna.

Sediment transport

According to Brahm's (Airy's) empirical law, the relationship between the mass of the particle m and the river flow velocity v required to transport it is as follows[9,10]

$$(m_1/m_2) = (v_1/v_2)^6,$$

where v_1 is the velocity required to transport a particle of mass m_1 and v_2 is the velocity required to transport a particle of mass m_2.

Conventionally, the particle size is denoted by the diameter and thus the particle sizes refer to the diameter of the particle. The soil characteristics of the Yamuna floodplain in Delhi (Figure 1) have a large spectrum of particle sizes (diameter) from 30 μm to 1 mm (ref. 6). For constant density, the mass is approximately proportional to third power of the diameter and thus the size of the transported particles is proportional to the square of the velocity (see Supplementary Information, online).

A flow velocity of 0.75 m/s can move only silt-sized particles of size up to ~ 60 μm (refs 8, 11). Using this as initial data, the relationship between velocity required to dislodge a particle of given size was mathematically extrapolated using Brahm's (Airy's) law, which resulted in a plot showing water flow velocity required to dislodge the different particle sizes (Figure 5). The relationship between flow velocity in the main river channel and total monsoon discharge through river Yamuna is given in Figure 6.

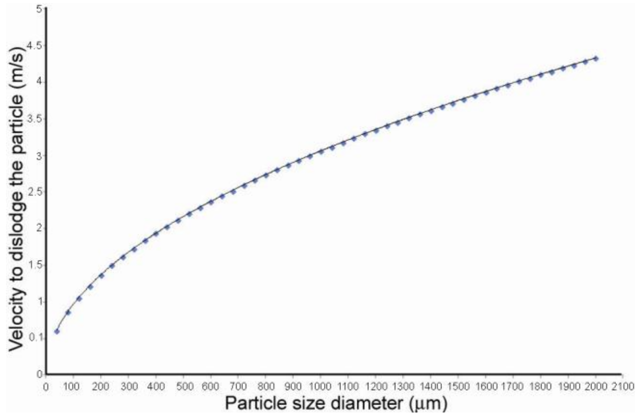

Figure 5. A plot of particle size versus velocity of flowing water required to dislodge the particle.

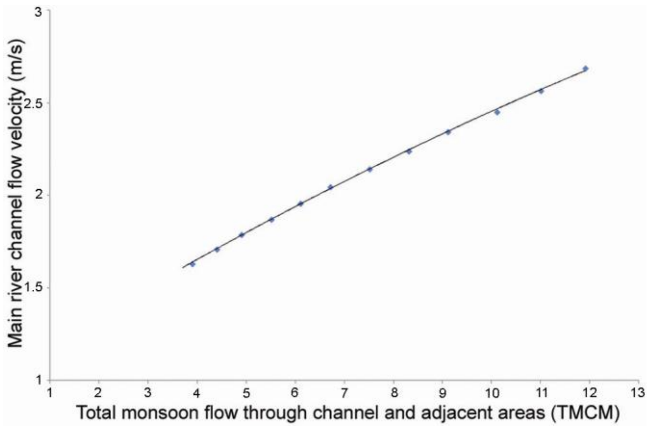

Figure 6. A plot of total monsoon flow through the main channel of river Yamuna and adjacent areas in Palla area, Delhi versus flow velocity in the main river channel.

The total monsoon discharge for a set of average monsoon river stages and the corresponding water flow velocity in the main channel and in the shoulder areas were estimated (Table 2). The average monsoon river stage of 208.9 m amsl corresponds to the flow of 3.9 TMCM (~ 36% of the total mean annual monsoon flow) through the river Yamuna (Table 2). The velocity in the main river channel at this total discharge was estimated at ~ 1.57 m/s (Figure 6 and Table 2). This velocity of flow can dislodge sediment particles of size ~ 265 μm (Figure 5).

The river channel is the faster flowing section of the river and thus will have a larger fraction of the larger soil

Table 2. Average monsoon flow through river Yamuna at Palla at different river stages

Main river Yamuna channel of width 80 m					Shoulder flow area adjacent to the main channel				Total		
River stage (m amsl)	Total column of water (m)	Velocity (m/s)	Particle size transported* (μm)	Discharge (m^3/s)	Average depth of flow of water (m)	Flow width (m)	Velocity (m/s)	Discharge (m^3/s)	Discharge (m^3/s)	Monsoon flow (TMCM)	% of virgin monsoon flow
208.9	2.5	1.57	265	316	0.96	250	0.79	191	507	3.9	36
209	2.6	1.64	290	344	1.01	263	0.84	223	567	4.4	40
209.1	2.7	1.72	310	374	1.06	276	0.88	259	633	4.9	45
209.2	2.8	1.8	340	405	1.11	289	0.93	299	704	5.5	50
209.3	2.9	1.88	370	439	1.16	302	0.98	343	782	6.1	55
209.4	3.0	1.97	415	475	1.21	315	1.03	393	868	6.7	61

*Particle size refers to diameter of the particle.

Table 3. Difference between average monsoon river Yamuna stage and peak flow river stage at Palla, Delhi

	Difference between average monsoon river stage and peak flow river stage (m)			
Year	July	August	September	Average
2008	1.1	1.1	2.1	1.4
2009	0.9	1.5	0.8	1.1
2010	2.1	1.6	1.3	1.7
Three year average (m)				1.4

Source: Irrigation and Flood Control Department, Delhi.

particles and grit from sewage discharge. An average monsoon flow of 5.5 TMCM (50% of the total mean annual monsoon flow) through river Yamuna corresponds to a river stage of 209.2 m amsl (Table 2). The velocity in the main river channel at this total discharge was estimated at 1.8 m/s (Figure 6; Table 2). This velocity of flow can dislodge sediment particles of size ~ 340 μm (medium sand[11]) (Figure 5). The main channel can thus be cleared of the larger and heavier sediments more efficiently at this flow velocity. Field-based observations show average monsoon peak flow to be approximately 1.4 m above the average monsoon river stage (Table 3). Based on this, the peak flow associated with the average monsoon river stage of 209.2 m amsl (corresponding to total flow of 5.5 TMCM) would be 210.6 m amsl. The flow velocity in the main river channel at the river stage of 210.6 m amsl would be 3.4 m/s (Figure 4). This river flow velocity is sufficient to dislodge particles of size ~ 1200 μm (1.2 mm; coarse sand[11]; Figure 5). Hence this river flow velocity will efficiently remove most of the heavy sediments and grit from the main river channel and prevent siltation and shallowing of the river channel.

The water flow velocity in areas adjacent to the main river channel corresponding to this monsoon flow of 5.5 TMCM at a river stage of 209.2 m amsl was estimated at 0.93 m/s (Table 2). This flow velocity can dislodge sediments particle of size ~ 95 μm (very fine sand[11]; Figure 5). Such well-sorted sediments will have higher permeability leading to enhancement in river bank storage during the monsoon floods.

Empirically, it is clear that the river is heavily silted and at present has a depth of only 0.6 m in summer. To remove all riverbed particles of diameter up to 1–2 mm (coarse sand to very fine gravel)[11] will require a monsoon flow larger than 50% (5.5 MCM), but we also have to balance this with reality (agricultural needs). A 50% (5.5 MCM) monsoon flow can dislodge particles of diameter up to ~ 1.2 mm; however, when such particles are transported and desilting occurs, the main channel will deepen enhancing the flow velocity. Consequently, even particles of larger size will be transported. We conclude that at least 50% (5.5 TMCM) of the monsoon virgin flow of river Yamuna is the flushing flow required in this stretch.

The delta and sea interface

The fertility of the delta and sea interface depends crucially on the transport of soil materials down to the river mouth, which in turn depends on having reasonable flushing flows. Strong flows are needed to avoid ingress of the sea, and preserve the mangrove interface. Thus, only if the flushing flow in the monsoon months is maintained can the environmental requirements of the delta and sea interface region be reasonably met.

Dolphins and biodiversity

The river dolphin and fish have disappeared from the Yamuna. The flow prior to Delhi (Figure 1) has a water depth of about 0.6 m through the peak summer months, which is too meagre to support a healthy fish population. The flow downstream of Delhi is mainly sewage, for this period, which is again not optimal. Besides, there is a variety of floodplain biodiversity which needs this minimum flow. If the mean annual environmental flow of river Yamuna is maintained at approximately 50–60% of its total annual flow, it may suffice for the ecological requirement of the river.

Recharge flows

The alluvial sandy soil in the Yamuna floodplain has aquifer parameters conducive for recharging the aquifer during a normal monsoon season[12]. The water flowing through river Yamuna, the groundwater in river bank storage (floodplain just by the side of the river) and the other water bodies are in dynamic equilibrium[13]. It is thus important to assess the desirable monsoon flow in river Yamuna required for proper recharging of floodplain aquifers.

The groundwater velocity through the sand in the Yamuna floodplain, at peak flood (river stage = 210.3 m amsl) has been estimated as 2.12 m/day. With this velocity, the lateral groundwater recharge beyond the flooded stretch over a period of three months (post-peak flood), would be about 200 m on either side (see Supplementary Information, online).

During the peak monsoon flow the river expands to a breadth of ~ 500 m and recharges the floodplain by gravity recharge. An additional ~ 400 m is recharged by lateral groundwater flow. Therefore, the total width of the floodplain recharged by the river during monsoon is ~ 0.9 km.

It is still not enough to recharge the whole floodplain, which stretches at least 5 km. 50% virgin flow will certainly widen the reach of the river, thus enabling more recharge.

Besides, wetting of the soil is also important as the good bacteria that can breakdown nitrates function only in the presence of water. These are strong reasons to maintain such ecological flows to preserve the recharge and quality of the water provided by the river, as aquifers are getting significantly impoverished.

Dilution flow

The city of Delhi is an urban mess, with a population touching 20 million which is way beyond its carrying capacity[14]. Downstream of Wazirabad barrage (Figure 1), a series of about 20 drains flow into the Yamuna making it a giant drain[15]. The city generates ~ 3.27 MCM/day of treated and untreated sewage[5]. The annual average biochemical oxygen demand (BOD) varies from 11 to 24 mg/l in the river water. The desired standard for BOD level in the river[5] water is 3 mg/l. Thus the average non-monsoon season BOD level is close to eight times more than the desirable level. This would require a dilution of eight times to make it fall into safe health limits, or a freshwater flow of over 20 MCM per day. Clearly, during the monsoon months there is adequate dilution flow to maintain health standards. But during the nine non-monsoon months this is not possible. Thus, in the non-monsoon months, there is no option but to treat the sewage of Delhi and reduce the BOD to no more than 5 mg/l. Thus, Yamuna needs comprehensive cleansing of sewage.

Minimum flow

A Memorandum of Understanding (MOU) between basin states of river Yamuna for sharing of the river water sets aside a minimum flow of 10 m^3/s throughout the year, for ecological purposes[16]. This amounts to a minimum freshwater flow in the river of 0.86 MCM/day, whereas we found that one needs about 6.6 MCM/day just to avoid algal choking.

Discussion

In case of the Yamuna, there are no dams but only barrages which are generally kept open during the monsoon, especially at flood or peak flood, when maximum soil transport occurs. This situation is then a good approximation of real-time virgin flow.

Unfortunately, the data we have been able to gather have been limited due to their non-availability in the public domain and thus the analysis here is at best localized and approximate. However, it is still significant. To our knowledge there have been no analyses earlier connecting monsoon discharge with average midstream velocities of flow required to transport the full spectrum (in size/mass) of soil particles found on the riverbed. In general, variation in the bed roughness, variation in the cross-sections of the river, presence of control structures such as dams, weirs, barrages, etc. can affect the flow at a location. However, we have avoided such complications in the present study.

Our findings, though particular to the Yamuna, will have an approximate validity for many monsoon rivers, in spite of the non-availability of relevant data. For example, the Godavari as it enters its delta has a total flow of about 110.5 TMCM, with only about 31.3 TMCM utilized[17] which means that only 28% of the flow is utilized. Further, the maximum (peak) velocity of flow at the Golden Arch Bridge at Rajahmundry has been found to be 5 m/s (ref. 18).

Thus, for the Godavari which has a healthy 72% free flow, the peak flow is well beyond 3.4 m/s that we found is required in the Yamuna to transport out soil particles of 1.2 mm; this happens when the average flow is over 50% of the total flow during the monsoon. This indicates that the appropriate minimum soil transport flow for the Godavari will also work out to about 50% of the total monsoon flow. Also, river Narmada at the Golden bridge in Bharuch, as it enters its delta has a total flow of about 45.6 TMCM, with about 23.6 TMCM utilized, which is nearly 50% of the total flow. This is close to the appropriate transport flow that we have found for the Yamuna. The peak flow velocities in this case also exceed 3 m/s. This supports the case that for the monsoon rivers in India in general, the norm for adequate soil transport and desilting requires over 50% of total monsoon flow.

Conclusion

We have attempted a detailed analysis to work out a genuine ecological flow that can maintain the health of a river and all its natural functions. Our finding is that a river needs close to 50–60% of the total flow to be safeguarded as free flow, regardless of the season. Briefly, during the monsoon, 50% of the free flow is needed for efficient soil transport (to avoid silting of the riverbed) and during the non-monsoon period, 60% of the free flow is needed to avoid algal choking. Since rivers in India are monsoon rivers, setting a single norm of 50–60% of the total flow as free flow, all year the round, would be appropriate for most rivers.

The long-term consequences of overexploiting a river and cutting flows will terminally affect the river and its surroundings. In this context the river Yamuna is already overexploited[19] (see Supplementary Information, online). We suggest that since the lean season use is mainly for agriculture, restoration of water flow in water scarce rivers can be accomplished by water harvesting, more efficient agricultural practices like drip irrigation and shifting more water-intensive agriculture (for example, rice and sugarcane) to water-surplus areas.

1. Soni, V., Gosain, A. K., Datta, P. S. and Singh, D., A new scheme for large-scale natural water storage in the floodplains: the Delhi Yamuna floodplains as a case study. *Curr. Sci.*, 2009, **96**, 1338–1342.
2. Soni, V. and Singh, D., Floodplains: self-recharging and self-sustaining aquifers for city water. *Curr. Sci.*, 2013, **104**, 420–422.
3. IWMI, Water Policy Briefing, Environmental flows. Planning for environmental water allocation, Report, International Water Management Institute, Sri Lanka, 2005, p. 8; http://www.iwmi.cgiar.org/Publications/Water_Policy_Briefs/PDF/wpb15.pdf (accessed on 3 August 2012).
4. Jha, P. K., Subramanian, V. and Sitasawad, R., Chemical and sediment mass transfer in the Yamuna river – a tributary of the Ganges system. *J. Hydrol*., 1988, **104**, 237–246.
5. CPCB, Water quality status of Yamuna River (1999–2005). Central Pollution Control Board, Government of India, 2006, p. 136.
6. Babu, C. R., Kumar, P., Prasad, L. and Agarwal, R., Valuation of ecological functions and benefits: a case study of wetland ecosystem along the Yamuna River corridors of Delhi Region, Report, Indira Gandhi Institute of Development Research, Mumbai, India, 2003, p. 185.
7. Hardy, T., Panja, P. and Mathias, D., WinXSPRO, a channel cross-section analyser. User's Manual Version 3.0. United States Department of Agriculture, General Technical Report RMRS-GTR-147, 2005; http://www.fs.fed.us/rm/pubs/rmrsgtr147.pdf (accessed on 15 May 2013).
8. Chow, V. T., *Open Channel Hydraulics*, McGraw-Hill, New York, 1959; in Chahar, B. R., Ahmed, N. and Godara, R., Optimal parabolic section with freeboard. *J. Indian Water Works Assoc.*, 2007, **39**(1), 43–48.
9. http://en.wikipedia.org/wiki/River (accessed on 24 March 2012).
10. Garde, R. J., *History of Fluvial Hydraulics*, New Age Publishers, 1995, p. 19.
11. Pettijohn, F. J., *Sedimentary Rocks*, Harper and Row Publishers, Inc., USA, 1984, p. 526.
12. Rao, S. V. N., Kumar, S., Shekhar, S., Sinha, S. K. and Manju, S., Optimal pumping from skimming wells from the Yamuna River flood plain in north India. *Hydrogeol. J*., 2007, **15**, 1157–1167.
13. Shekhar, S. and Prasad, R. K., The groundwater in Yamuna flood plain of Delhi (India) and the management options. *Hydrogeol. J*., 2009, **17**, 1557–1560.
14. Soni, V., Water and carrying capacity of a city: Delhi. *Econ. Polit. Wkly*, 2003, **38**, 4745–4749.
15. Shekhar, S. and Sarkar, A., Hydrogeological characterization and assessment of groundwater quality in shallow aquifers in vicinity of Najafgarh drain of NCT Delhi. *J. Earth Syst. Sci.*, 2013, **122**(1), 43–54.
16. NIH, Comprehensive and integrated hydrological study of NCT Delhi. National Institute of Hydrology, Roorkee, 2006, p. 106.
17. Central Water Commission Factsheet, 2011.
18. http://en.wikipedia.org/wiki/Godavari_Arch_Bridge (accessed on 15 November 2013).
19. Khosala, R. and Soni, V., Delhi Mumbai corridor, a water disaster in the making? *Econ. Polit. Wkly*, 2012, **47**, 15–17.

ACKNOWLEDGEMENTS. We thank Sri Vikas Jayani for help in verifying the river channel data using remote sensing imagery, and Dr S. V. N. Rao, WAPCOS, Hyderabad for support and cooperation. V.S. thanks the UGC and ICTP, Trieste, Italy for support.

Received 3 June 2013; revised accepted 6 December 2013