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title: **The impact of regulated river-flow on the travel-time and flow-path of bank filtrate in Haridwar, India**

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INTRODUCTION

In Haridwar, riverbank filtration (RBF) accounts for more than 35% of the total drinking water production of around 64,000 m^3/day for 200,000 permanent residents and an additional approximate 330,000 pilgrims visiting the city daily (Dash et al., 2010). Even when the demand for drinking water peaks to supply up to 8 million additional pilgrims in a single day, such as during religious festivals like the Kumbh and Kanwar Melas, the abstracted water only requires disinfection. Throughout the year the flow in the Ganga River and Upper Ganga Canal (UGC) is controlled by the Bhimgoda Barrage (or weir) on the river, and an intricate system of smaller weirs and escape channels on the UGC to the south, to ensure sufficient discharge in the canal for irrigation and religious rituals of bathing and worship. However, for a 20-day period annually in Haridwar (October–November), the UGC receives no flow in order to permit dredging and levelling of the fluvial sediments, especially at the bathing sites which are located between the RBF wells and the canal. During this period, the production of these wells decreases significantly.

This study investigates the impact of the three-month monsoon (July–September), the canal closure and the normal surface water levels (November–June) in the UGC and Ganga River on the travel time and flowpaths of bank filtrate.

WATER SUPPLY AND HYDROGEOLOGY OF HARIDWAR

Until the end of 2009, the total 64,000 m^3/day drinking water production of the city of Haridwar was obtained from 16 large-diameter partially penetrating bottom-entry (caisson) wells abstracting bank filtrate (Fig. 1) and 31 vertical wells abstracting mainly groundwater. Out of these, twelve caisson wells are situated along a 3.3-km-long and 190-310–m-wide stretch of land between the UGC and the Ganga River, at a distance of 3–115 m from the canal and its escape and feeder channels. These wells receive a high proportion of bank filtrate (>70%) because of a significant natural gradient between the UGC and the Ganga River. Four more wells are situated approximately 10–50 m from the Upper Ganga Canal to the north of Pant Dweep Island and further upstream within 70 m of the Ganga River. In preparation to meet the large increase in drinking water demand during the huge religious gathering of the Kumbh Mela in January–April 2010, six more new caisson bank filtrate wells of a similar design to the existing wells (Fig. 1) and 19 new vertical wells became operational in January 2010 and will be permanently integrated into the water supply network (Sandhu et al., 2010). The depth of the caisson wells is 7–10 m below ground level and their discharge ranges from 0.01–0.047 m^3/s. The abstracted water is chlorinated at the wells and then routed directly into the distribution network. Previous studies on the quality of the abstracted bank filtrate by the caisson wells have demonstrated that the RBF scheme in Haridwar is a sustainable source of clean drinking water (Thakur et al., 2009; Dash et al., 2010).

On Pant Dweep Island and the area immediately to the island's north (Fig. 1; enlarged area), nine caisson wells (wells 16, 18, 26, 40 and the 2010-built wells of Bhopatwala 1, 2 & 3, Pant Dweep New and Kangra Dweep new) operated by Uttarakhand Jal Sansthan (UJS; Uttarakhand state water supply company) abstract around 518–2,530 m^3/day of raw drinking water per well. The operation of the wells (that use air-cooled centrifugal pumps) is discontinuous depending on the yield and water demand. For instance, while well 40 operates for at least 19 hours/day and is shut down for 5 hours to allow the pumps to cool during periods of low water demand, well 18 operates for around 8-10 hours/day due to insufficient yield (Dash et al., 2010).

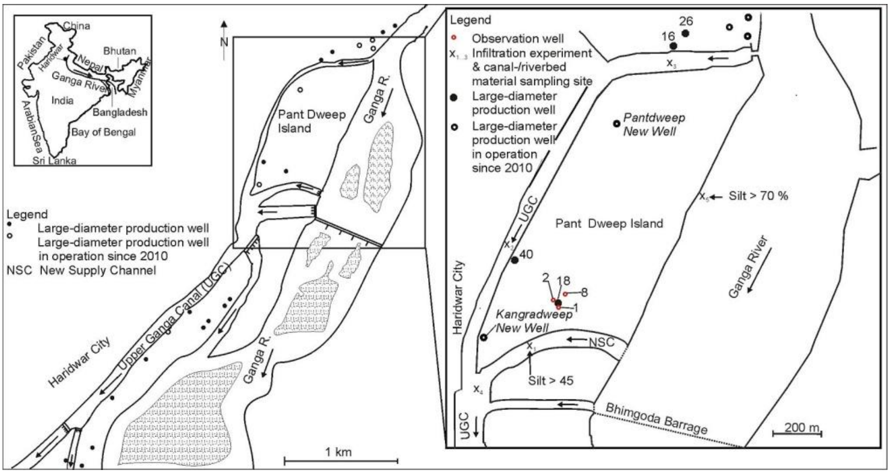

Figure 1. Study area in Haridwar and location of large diameter (caisson) bank filtrate production wells

The Pant Dweep Island was originally influenced solely by the seasonal variation in the flow of the Ganga before the Bhimgoda Barrage was built and thus was also inundated at times by the river resulting in varying rates of sediment deposition. The deposits are overlain by Holocene fluvial boulders (Dash et al., 2010). Grain size distribution analyses of borehole material from two monitoring wells (Fig. 1; 1 & 2 in enlarged area) constructed in 2005 revealed a 21-m-thick unconfined aquifer comprising fluvial deposits of fine to coarse sand and gravel in the upper 12 m followed by finer material comprising mainly silty sand (Sandhu et al., 2006). According to Dash et al. (2010), the hydraulic conductivity (K) calculated after Beyer (1964) for borehole material up to a depth of 14 m below ground level varies from 1.9×10^{-4} to 4.7×10^{-4} $m\cdot s^{-1}$. On the other hand, pumping tests conducted on wells 8, 18 and 40 (Fig. 1) resulted in K values of 2.3×10^{-4}, 7.1×10^{-5} and 1.2×10^{-4} $m\cdot s^{-1}$ respectively. In comparison to well 8 and 40, the very low K value for well 18 is attributed to well clogging and is not a representative value for the aquifer as a whole.

Dash et al. (2010) describe the aquifer as being in direct hydraulic contact with the UGC, New Supply Channel (Fig. 1; NSC) and Ganga River. Results from infiltration experiments in the UGC (Fig 1; locations x_1...x_3, in March 2007), using a piezometer inserted into fine sand lodged between fluvial boulders in the bed of the UGC, gave K values ranging from 0.4×10^{-5} to 8×10^{-5} $m\cdot s^{-1}$. Grain size distribution analyses of superficial UGC bed material (Fig 1; location x_4, in October 2009) resulted in K values of 1.2×10^{-4} to 7.4×10^{-3} $m\cdot s^{-1}$ (after Hazen, 1893). Considering that the UGC has a gradient of around 3‰ along the northern and western boundary of Pant Dweep, and that its bed exhibits a K value nearly equivalent in magnitude to the adjacent aquifer, the clogging of the UGC can also be considered negligible. The removal of the upper UGC bed material by dredging, when the canal is closed for 20 days annually (usually in October–November), and high flow velocity (>1 $m\cdot s^{-1}$) especially during monsoon (July–September) also limit clogging in the UGC. However, the beds of the Ganga River in the reservoir of the Bhimgoda Barrage along Pant Dweep's eastern boundary and the NSC along the island's southern boundary have a high silt content of 40–70% (Fig. 1; sites x_1 & x_5), which likely limits the hydraulic connection with the aquifer to a certain degree. Additionally, the K value of the bed material of the NSC (Fig. 1; site x_1), determined from infiltration experiments, ranges from 0.2×10^{-6} to 9×10^{-6} m·s^{-1}. This is representative of fine sediment material deposited by the barrage outflow as a result of the lower flow velocity (<1 m·s^{-1}) and gradient compared to the UGC.

TRANSIENT-STATE GROUNDWATER FLOW MODELLING

Description of groundwater flow model

To get an improved understanding of the boundary conditions and the travel time and flow-paths of the bank filtrate abstracted by the drinking water production wells, a three-layered groundwater flow model was constructed from the field observations described in section 2 using Processing MODFLOW version 5.3.0 (Chiang, Kinzelbach, 2001) for the existing as well as new caisson wells on Pant Dweep Island and to its north on the bank of the UGC and Ganga River (Tab. 1).

Table 1. Main features of the groundwater flow model for Pant Dweep Island, Haridwar.

Parameter	Characteristics				
Geometry	Area: 2400 m × 2800 m; 37 rows, 46 columns. Cell-size: 5 m × 5 m to 100 m × 100 m				
Boundary conditions	River stage: Field water level measurements on 01.03.2008				
	Kriver bed: UGC = 1×10^{-4} ... 2×10^{-3} m s^{-1}				
	NSC = 5×10^{-5} ... 4×10^{-4} m s^{-1}				
	Ganga River: = 1×10^{-6} ... 8.3×10^{-5} m s^{-1}				
	Actual production well discharges = 0.019–0.037 m^3 s^{-1}				
	Discharges normalised for 24 hours for model (QAbstraction) = 0.013–0.029 m^{3}s^{-1}				
Time	Stress period	Time step (Length = 30 days/time step)	Month	Remarks	Change in boundary conditions
	1	3	July–September	Monsoon: Increase in surface water levels compared to 01.03.2008	UGC +0.6 m NSC +0.9 m Ganga + 1.7 m
	2	1	October	UGC closed (deactivated)	QAbstraction decreased by 50% (all wells)
	3	8	November–June	Normal post- & pre-monsoon	Normal post- & pre-monsoon conditions
	4	3	July–September	As in stress period 1	As in stress period 1
Initial heads	Interpolation of surface and groundwater level measurements of 01.03.2008				
Aquifer parameters	Kx = Ky = 3.7×10^{-4} ... 5.0×10^{-4} m s^{-1}; Kz = 2.6×10^{-5} m s^{-1} (upper & middle layer)				
	Kx = Ky = 2.7×10^{-4} m s^{-1}; Kz = 2.6×10^{-5} m s^{-1} (lower layer)				
	Specific storage = 0.001; specific yield = 0.25; effective porosity = 0.30				

The cell sizes of the nine production wells in the model domain were refined to a finer resolution having a range of 5 m × 5 m to 50 m × 50 m. The surface and groundwater levels measured on and around Pant Dweep Island on 01.03.2008 were interpolated and assigned as initial hydraulic heads and used for the river stage elevation of the Ganga, UGC and NSC. To account for the partial penetration of the caisson wells, the bottom elevation of the upper layer of the model corresponds to the bottom of the productions wells. The bottom elevation of the middle (second) and lower (third) layers corresponds to the stratigraphy interpreted from the borehole logs of the two monitoring wells on Pant Dweep Island.

All surface water levels were simulated using the river boundary condition. A uniform river bed conductance of 0.5 $m^2 s^{-1}$ was assigned to the cells of the UGC. Depending on the variation of the cell dimensions, this conductance value corresponds to a hydraulic conductivity of 1×10^{-4} m s^{-1} to 2×10^{-3} m s^{-1} (Tab. 1) that closely reflects the hydraulic conductivity determined from the grain size distribution analyses of the UGC bed material and infiltration experiments (Sec. 2.2). The conductance of the bed of the NSC to the south corresponds to a lower hydraulic conductivity of 5×10^{-5} m s^{-1} to 4×10^{-4} m s^{-1}, thereby accounting for the higher silt content lodged between the fluvial boulders as a result of the NSC's low gradient. A hydraulic conductivity of 1×10^{-6} m s^{-1} to 8.3×10^{-5} m s^{-1} was used to calculate the riverbed conductance of the Ganga in the reservoir of the Bhimgoda barrage to the east of Pant Dweep Island to account for clogging and the high deposition of silt. Due to the variation in the discharge and the duration of daily operation between the wells, the actual discharges and pumping hours of the nine production wells were normalised for twenty-four hours, causing the model discharge values to range from 0.013 to 0.029 $m^3 s^{-1}$ (Tab. 1).

Simulation of scenarios

The transient groundwater flow model was run for one complete continuous cycle to simulate a 15-month period that starts with the monsoon at the beginning of July in the current year (stress period 1, time step 1) and ends at the end of the monsoon in the following year (stress period 4, time step 15) as shown in Tab. 1. During this cycle the Upper Ganga Canal closes for 20 days (usually October-November) after the monsoon in the current year ends (stress period 2, time step 4). After the UGC reopens, whose flow s regulated throughout the year, no major changes occur in the water level of the canal till the onset of the monsoon in July of the following year (stress period 4, time step 13). The inclusion of two monsoon phases was necessary in order for the model to attain the starting groundwater levels (that were simulated in stress period 1, time step 1) again after a one year cycle.

TRAVEL TIMES AND FLOWPATHS OF BANK FILTRATE

For the production wells located close to the UGC, the travel time of the bank filtrate from the canal to the wells is less than a month when the simulation starts at the beginning of the monsoon in the current year (Fig. 2A). Towards the end of the monsoon in September, an increase in the groundwater levels on Pant Dweep Island of more than 0.5 m can be observed, as depicted by the general southward movement of the groundwater contours (Fig. 2B). The wells close to the UGC also begin to receive a higher proportion of bank filtrate at this stage. Then, the groundwater levels and flow velocity decrease around the wells close to the UGC during its closure (Fig. 2C) and in the period of resumption of operation (Fig. 2D). However, within one year of operation, all wells receive bank filtrate (Fig. 2E) whose proportion is sustained by the second monsoon season accompanied by higher groundwater levels on Pant Dweep Island (Fig. 2F).

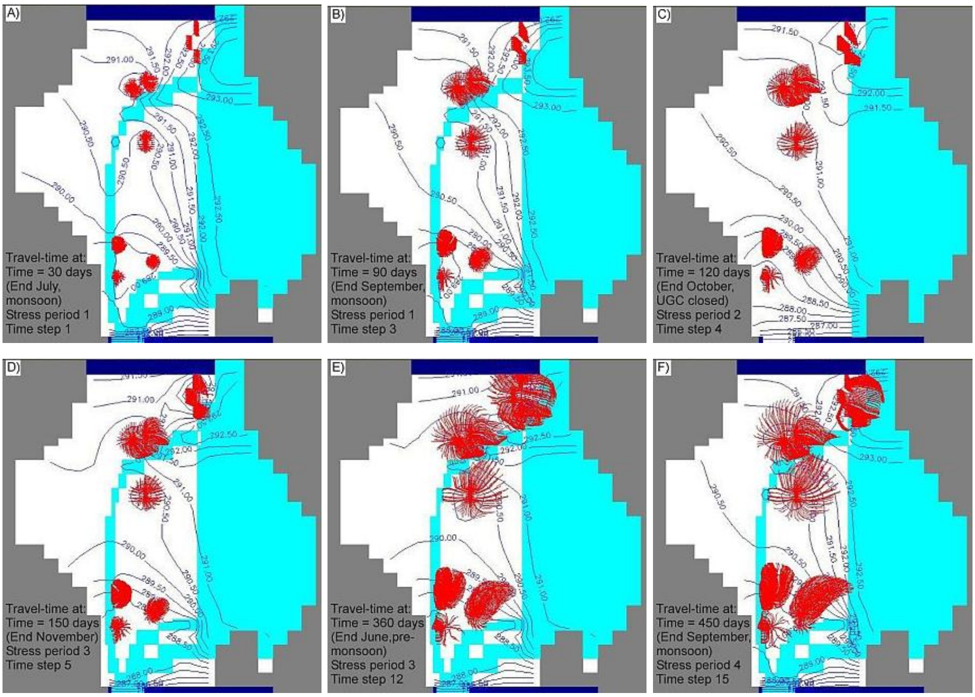

Figure 2. Travel times and flowpaths of bank filtrate to production wells on and to the north of Pant Dweep Island, Haridwar, under different surface water flow scenarios.

CONCLUSION

The closure of the UGC has no long-term adverse impacts on the volume and quality of bank filtrate. But during the 20-day closure, the operating hours of all wells decrease and thereby the production rates normalised for 24 hours also decrease (all pumps operate at a single frequency). The increased groundwater abstraction to compensate for the reduced bank filtrate production is sustainable because the parent groundwater is originally bank filtrate infiltrated more than 2 years prior along the river upstream of the Bhimgoda Barrage where the flow remains significant throughout the year. The annual UGC maintenance closure also disturbs the clogging layer of the canal in places where the dredging occurs. While this could increase the yield of the wells, it could also permit greater and more rapid entry of contaminants into the groundwater ultimately abstracted by the drinking water wells. As the level of dissolved organic carbon and coliform bacteria is comparatively low in the Ganga upstream of the Bhimgoda Barrage, one of the main risks of the dredging of the UGC bed could be from shock loads of organic compounds that may accidentally enter the river.

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