Application of MODFLOW for groundwater Seepage Problems in the Subsurface Tunnels

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ABSTRACT

The construction of subsurface structures such as Tunnel beneath the water table causes the groundwater seepage into the structure and impacts the stability of the structure. A 2.483 km long railway Tunnel was constructed between Katara and Udhampur in Jammu and Kashmir province of India. It is occupied by alluvium with scanty exposures of sandstone belonging to the Middle Shiwalik group. A huge amount of infiltrated water from the perennial canals and agriculture fields is entering the Tunnel. In addition to this, dry Nala/Palaeo channel across the Tunnel alignment contributes significant groundwater seepage during rainy season. A finite difference based groundwater flow model was constructed using the inferences from hydro-geo-morphological features and geologic lineaments to estimate the groundwater seepage and find out the possible solution. The computed flow model indicated that Tunnel would receive groundwater seepage of 78,133 m³/day. The analysis of the model results revealed that 500 lateral perforated pipes of 5 m in length at an interval of 2 m with an annular space filled with highly permeable geo media can drain out the seepage water. The suggested perforated pipes were successfully installed in the Tunnel. They were effective in draining out the groundwater seepage.

INTRODUCTION

In general, in any tunneling operations, the most important problem is groundwater seepage from the aquifer, if the tunnel alignment is below the water table. In addition to this, surface water bodies such as rivers and streams, land use pattern such as irrigation with surface water and groundwater also contribute additional seepage into the Tunnel. Destructions due to water seepage into Tunnels that include reduction of rock mass stability around the Tunnel increase pressure on temporary and permanent supporting systems, reduction of operational rate leading to financial losses (Goodman et al., 1965; Freeze and Cherry, 1979; Shimojima et al., 1993; Vincenzi et al., 2009; Vikas Thakur, 2009; Youngs, 2004). The dramatic groundwater drawdown through seepage into the Tunnel may cause land subsidence, water table decline and other environmental problems (Molinero et al., 2002).

The actual prediction of groundwater seepage and its impacts is highly difficult due to the complexities associated in recognition and exact determination of collective factors on groundwater flow. It is also very important to design a proper drainage system to drain out the seepage in addition to the estimation of groundwater seepage. Hence, the analytical and numerical modelling methods have many advantages in estimation of groundwater infiltration into Tunnels due to their simplicity and practical applicability (Kitterod et al., 2000; Farhadian et al., 2012). The analytical methods are very simple and use basic equations for computations. On the other hand, numerical methods

are not simple with reference to computation and need more information about boundary conditions and material properties. As a result, numerical methods are more complicated and their application needs more time and data. However, numerical methods provide more accurate results compared to analytical methods. The most important studies to estimate the rate of groundwater seepage into tunnels using analytical methods are well explained by Heuer, 1995; Lei, 1999; El-Tani, 1999, 2003; Karlsrud, 2001; Park et al., 2008; Katibeh and Aalianvari, 2009; Farhadian et al., 2012. During last two decades, numerical methods such as finite element and finite difference methods have been extensively used to simulate groundwater seepage into tunnels and mines (Kitterod et al., 2000; Bagtzoglou and Cesano, 2007; Sekhar and Mohan Kumar, 2009; Zaidel et al., 2010; Surinaidu et al., 2013a; Mitja Janža, 2010; Zhu and Wei, 2011; Wanghua Sui et al., 2011; Stefano Lo Russo et al., 2013; Xiaojuan Qiao et al., 2011), to estimate the groundwater balance (Ely et al., 2011; Varalakshmi et al., 2014; Surinaidu et al., 2013b, 2014a, 2014b).

The present study area is located in Udhampur district in the Jammu and Kashmir province of India. Rail India Technical and Economic Service (RITES) have constructed a 2.483 km long Tunnel between Udhampur and Katara at a depth of 37 m below the ground surface. The entire region is occupied by alluvium comprising of sand, gravel, pebbles and boulders with varying proportions. The study area is drained by numerous perennial rivers, streams and paleao channels. The collective contribution of all these factors is
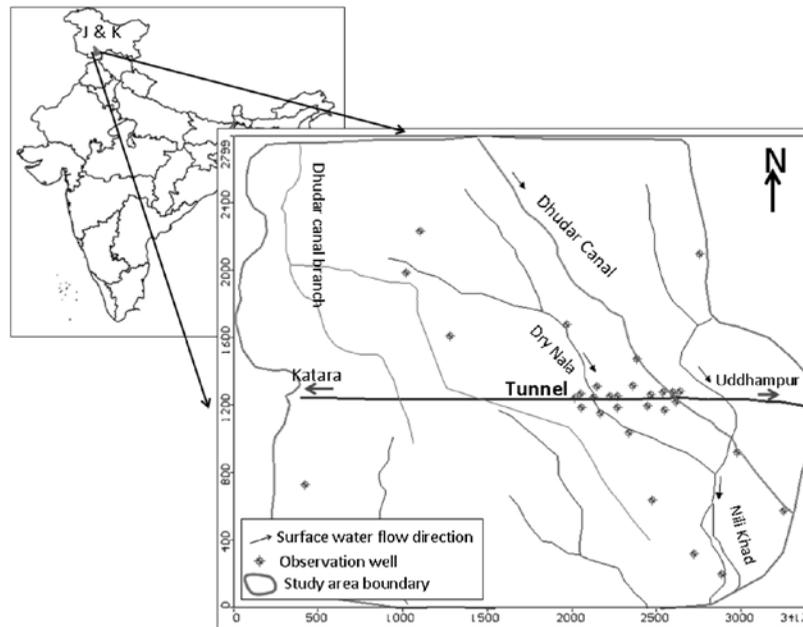
Figure 1. Location of the study area, Tunnel alignment and observation wells, Uddhamur district, Jammu and Kashmir, India (X and Y axis are in m)

the main source of groundwater seepage into the Tunnel. As a result, the movement of the trains between Katara and Udhampur districts was severely disturbed. In the present study, a finite difference based groundwater flow model using MODFLOW (McDonald and Harbaugh, 1988) with Visual MODFLOW graphical interface was constructed to estimate the groundwater seepage into the Tunnel and to provide the possible solution to drain out the seepage for the protection of the Tunnel.

Location And Description Of The Study Area

The study area is situated in the central part of Udhampur district in Jammu and Kashmir, India and falls between 32°55″ - 33°00″ E and 75°00″ - 77°10″ N in the Shiwalik range of Himalayas covering an area of 10.64 km². The constructed tunnel is located between the Dhudhar and Nili rivers at a length of 2.483 km (Fig. 1). The altitude ranges between 551 m to 1500 m above mean sea level (amsl). The climate is sub tropical and the average annual rainfall is 2400 mm. The summer temperature does not cross 40°C while in winter it records 2°C and even less (Gurunadha Rao et al., 2011).

Geology And Hydrogeology

The region falls under the Middle Siwalik Group (GSI, 2007) forming a part of the extra peninsular belt covered by the sedimentary rocks of frontal belt affected by the fold thrust movement during the terminal phase of the

Himalayan orogeny. It falls in the north of the Mastgarh anticline and is in close proximity to the Reasi thrust running in the North West - South East direction. In these Shiwalik formations, sandstone and clay layers are overlaid by quaternary to recent alluvium comprising sand, silt, clay, pebbles, cobbles and boulders with varying proportions (HPRSC, 2010). In the eastern edge of Tunnel towards Udhampur, a huge cavity was formed due to collapse of the surface material. The behavior of the collapse of the material inferred that Tunnel alignment might be passing through a buried/old channel which has been subsequently filled up with boulders, gravels and soil, naturally. The dry Nala crossing the centre of the alignment seems to be the remnant of the old Nala and the maximum thickness of the deposited material was about 45 m. The litholog of the 37 m bore well did not indicate any bed rock. The detailed geological mapping along the Tunnel between Udhampur-Katara has revealed that major portion of the Tunnel alignment was occupied by alluvium with scanty exposures of sandstone belonging to Middle Shiwalik Group.

The general trend of the rock mass is from Katara to Udhampur and dipping 10° to 20° towards South East direction. The Tunnel is aligned almost right across the trend of the rock mass with gentle dip ranging from 18° to 25° towards the East. The sandstone is massive in nature and sparsely jointed. Besides, small out crops of terrace deposits (2 to 5 m thick) represented by boulders, gravels, pebbles with minor fine sediments in the form of clay have been identified along both the banks of Nilli Nala and a dry seasonal Nala crossing the alignment. The excavation

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of the Tunnel of 2.483 km length and 5m width of 5 m between Udhampur to Katara reveal brownish grey massive coarse grained sandstone with some occasional pebble and clay bands belonging to Middle Shiwalik Group. As soon as the excavation reached a length of 2.5 km from Katara end, a huge collapse occurred with the movement of highly unconsolidated and saturated material consisting of boulders, gravels, pebbles and clayey material. Therefore, a funnel shaped cavity was formed with a visual depth of around 12 m from the top. The excavation from the Katara end indicated greenish grey to grey fine grained sandstone, siltstone with thin bands of red clays and clay stone belonging to the lower Shiwalik Group. Middle Shiwalik group of medium to coarse grained sandstone with occasional subordinate clay bands are identified at the end of the Katara Tunnel portion. The Dudhar branch canal with huge discharge flows at centre of the Tunnel alignment from North to South irrigate cultivated fields. As the area is occupied by highly porous material, heavy recharge through the surface water infiltration, particularly during monsoon and return flows from canal irrigation enter into the groundwater system. The dry Nala/Palaeo channel as mentioned above crosses the alignment and has a considerable flow of water during rainy season. But as soon as the rain stops, Nala drie out immediately indicating very high recharge through highly porous material (GSI, 2007).

Drainage Pattern, Geomorphology And Lineaments

The drainage pattern in the area is controlled by the structural elements such as fractures and faults exhibiting four types viz., dendritic, parallel to sub-parallel and braided channels. Dendritic drainage pattern is developed in the northern part of the Dudhar and Nili khad in the upstream. However, the drainage trend becomes more or less parallel to the bedding plane surface indicating a definite control on the subsurface features in the downstream area of these Nalas. Drainage in the east of Nili khad area exhibits dendritic pattern. The interpreted IRS P6 - LISS-III satellite imagery indicates that the course of Nili khad exhibits braided drainage pattern consisting of distributed channels that normally shift during successive flooding events in the area. A similar drainage pattern is exhibited in Kambaldanga ephemeral stream just below the major lineament. It is observed that in the close proximity of the lineament, the drainage pattern is deep owing to the steep dip of in-situ sandstone formation.

The tectonic activity followed by the action of river water is responsible for dominant processes of weathering, erosion and depositions to form the different geomorphology in this area. The major geomorphic units in the area such as fluvial plain, terrace scarps, structural scarps, structural terraces, structural hills, landslide scarps, and alluvial fan

(Fig. 2) are drained by an ephemeral stream, a tributary of Nili khad. The lower course of Nili khad and the stream in the Kambaldanga are cut across by linear fractures. The entire area is uplifted near the lower course exposing the Shiwalik formation that resulted in the formation of the flat agricultural tract in the upper catchment filled with unconsolidated fluvial material leading to high infiltration due to its higher porosity and permeability. A Gorge has been formed in the absence of old fluvial material in the lower reaches of the Nili khad. The major lineaments are oriented in NW-SE and NE-SW directions across the Dudhar khad and the Nili khad. The presence of intersected and deep fractures in the Kambaldanga and Eastern edge of the Tunnel leads to more surface water recharge into the groundwater system (Fig. 3).

Groundwater Conditions

Groundwater recharge is very high in the Eastern part of the Tunnel and along the dry Nala due to the presence of alluvium/soil underlain by highly porous strata. The discharge data collected in the tunnel reveal that maximum discharge of groundwater occurs during July to September which reduces considerably to minimum during November to May. The depth to groundwater levels revealed a variation from 22 - 40 m (bgl) along the Tunnel alignment during May 2008, and raising upto 18 - 35 m (bgl) in the month of August 2008. The average water level rise in the month of August is 4 m.

METHODOLOGY

The hydraulic conductivity of the aquifer is estimated by conducting pumping tests at two locations in the area by RITES and reported average conductivity as (refer Fig. 1) 8.2 m/day. The annual groundwater recharge is estimated by using water level fluctuation method is

Recharge (mm) = $S_y * D_h * $ Area (Chatterjee and Purohit, 2009).

S_y - Specific yield, D_h – Water level rise in monsoon season

The specific yield of these formations varies from 0.04 – 20% in this area and the average specific yield is considered as 9% to estimate recharge (Chatterjee and Purohit 2009).

The finite difference based groundwater flow model is constructed in the steady state condition using Visual MODFLOW (Guiguer and Franz, 2006) using pertinent hydrogeologic data. This finite difference block-cantered modelling package can simulate steady-state and transient groundwater flows for different hydrogeological systems (McDonald and Harbaugh, 1988). The subsurface environment of earth constitutes a complex three dimensional heterogeneous hydrogeologic setting. The
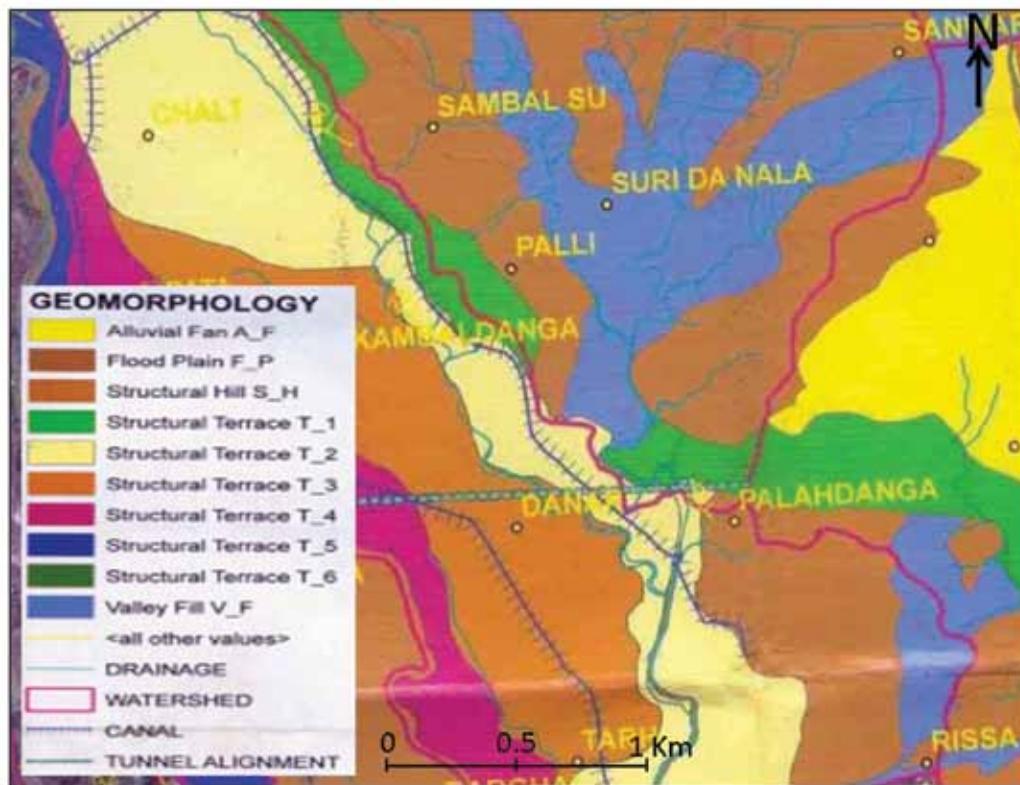
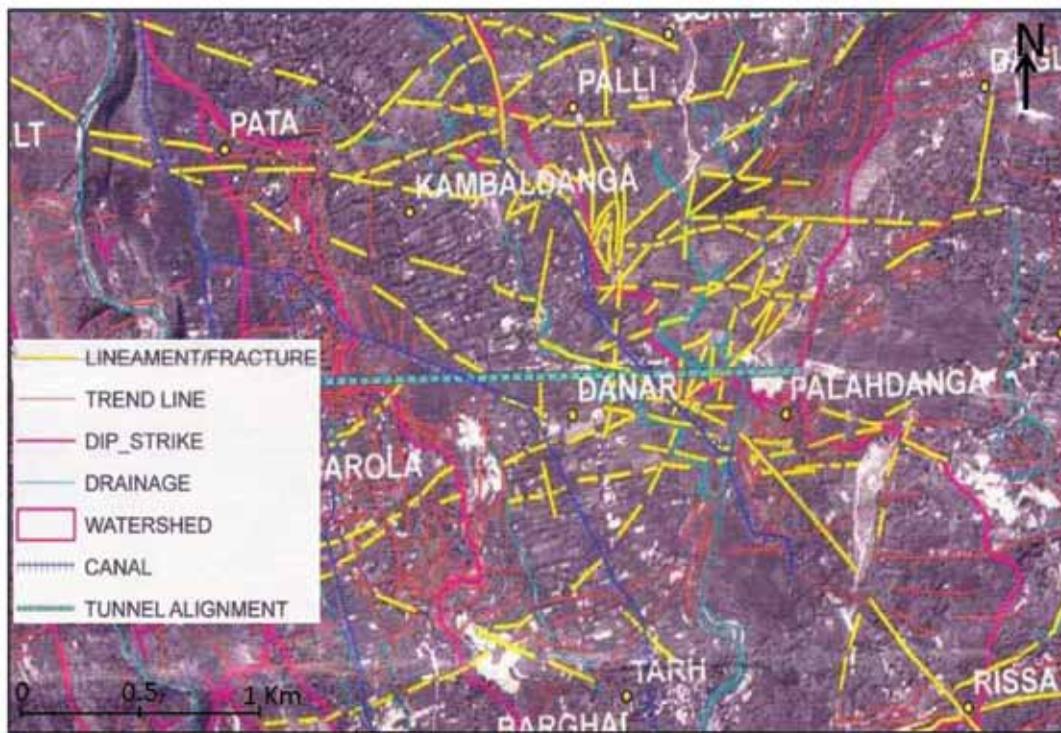**Figure 2.** Geomorphology in the study area (Source, HSPSC, 2010)

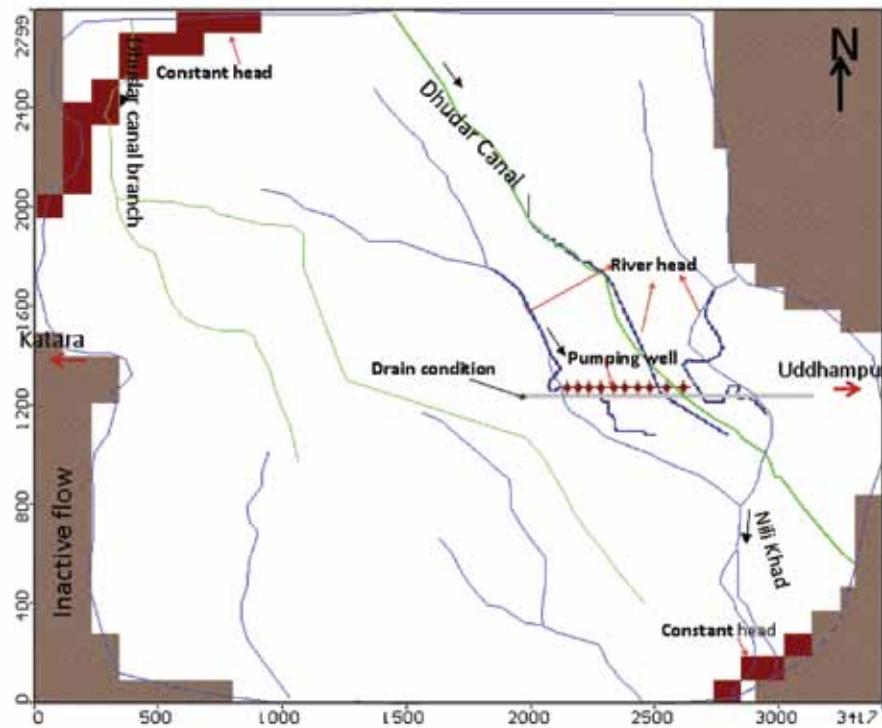**Figure 3.** Lineament pattern in the study area (Source, HSPSC, 2010)

Figure 4. Boundary conditions in the study in the flow model (X and Y axis are in m)

subsurface conceptual model of the present study area was developed based on borewell geologic logs and hydrogeology of the area. The collected GIS-based information was synthesized in a finite difference numerical model (MODFLOW) and calibrated under steady state condition assuming an equivalent porous medium approach (Singal and Gupta, 1999). The model was simulated as two layer aquifer system with 47 m thick first layer and 5 m thick second layer. The entire study area covering about 10.64 km^2 is divided into 161 rows and 189 columns with two conceptual layers. The cell size in the model varies from 100 m^2 to 50 m^2 and it is 2.5 m^2 along the Tunnel alignment in the groundwater flow model.

RESULTS AND DISCUSSION

Boundary conditions and calibration

The constant head boundary condition is used in the North West corner and also in the South East direction with relevant groundwater elevations to indicate lateral inflows into the area and out flows from the area. River head boundary condition is used for dry Nala, Nilli khad stream and Dudhar canal distributaries to simulate stream and aquifer interaction. The average groundwater level rise at the end of August is 4 m. Therefore, estimated average recharge is 320 mm and it is simulated with

recharge package in the model. To simulate the potential groundwater seepage into the Tunnel, the drain head condition (Polubarinova-Kochina, 1962; Batelaan and De Smedt, 2004) is specified, which is equal to the elevation of the corresponding cells/ Tunnel invert level varying from 745 m (amsl) to 739 m (amsl) (Fig. 4). However, the drain conductance is specified as a user-defined coefficient with typically large values indicating low resistance to flow (Batelaan and De Smedt, 2004). In the study area,the drain condition was simulated along the Tunnel with a conductance that varies from 150 to 250 m^2/day. The observed groundwater heads at 28 observation wells in the month of August 2008 were considered to calibrate the flow model.

The model calibration has been achieved by adjusting hydraulic conductivity and recharge in the study area. The conductivity and recharges are adjusted for better calibration to match the observed groundwater heads with computed heads in the flow model. The analysis of the lineaments such as fractures will improve the model calibration (Li et al., 2009). Therefore, geomorphological features and lineaments described in section 4 are considered to distribute the permeability and recharge during the calibration process by considering estimated recharge and conductivity. The permeability in the Eastern and Western part of the area was considered as 3 m/day and 2 m/day respectively to represent hilly regions while
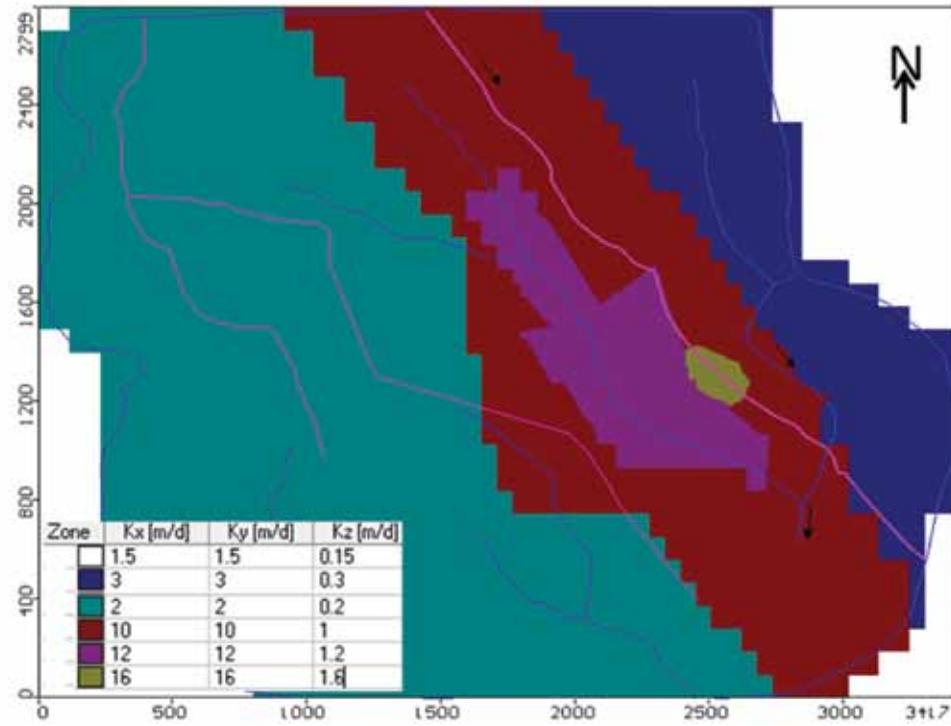
Figure 5. Distribution of the conductivity in the study area (X and Y axis are in m)
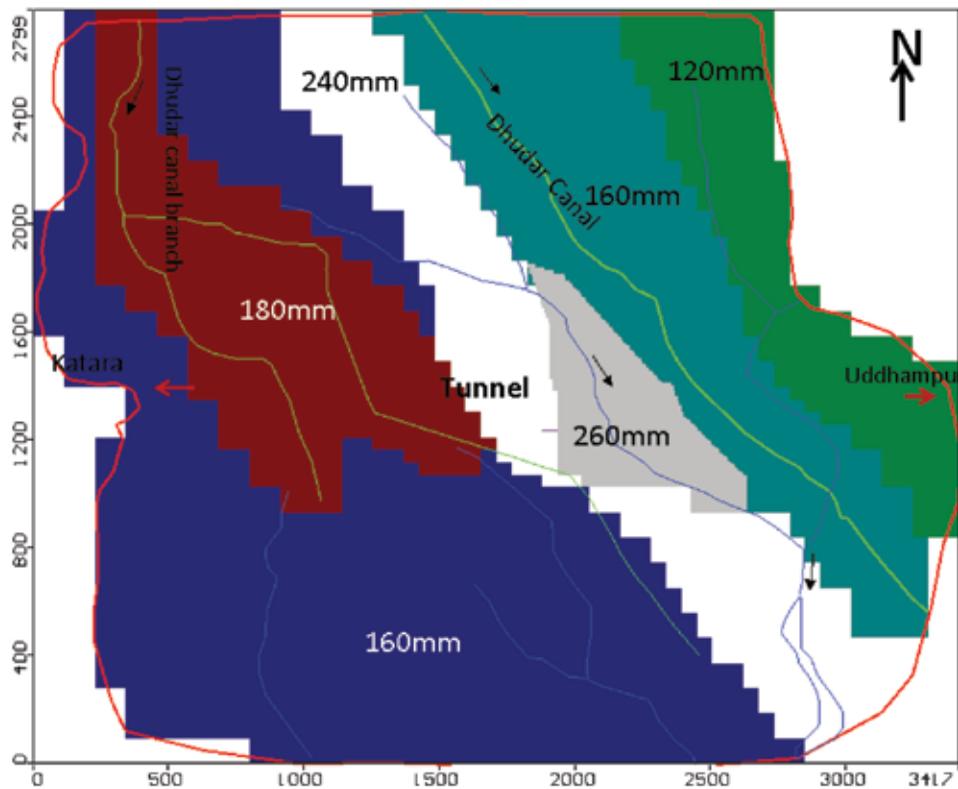

Figure 6. Distribution of the recharge in the study area (X and Y axis are in m)

10m/day was considered in the peripheral area along the Dhudar canal representing good saturation conditions. However, in the central part of the area, it was 12 m/day to represent dense fractured networks. The cavity formed in the Eastern part of the Tunnel is occupied by coarse grained material indicating highly porous in nature and hence the permeability of the first layer was considered as 16 m/day (Fig. 5). A permeability of 1.5 m/day was considered for second layer to represent hard sand stone formation. The annual groundwater recharge has been relatively modified based on hydrogeology and lineaments in the study area. The distributed annual recharge in the area varies from 120 mm to 260 mm. The annual groundwater recharge in and around Kambaldanga varies from 240 – 260 mm revealing the control of lineaments/fractures and palaeo channel on recharge in this area. The recharge around Dhudar canal peripheral area is considered as 160 mm. It is 120 mm in the eastern edge and 160 mm in the western edge (Fig. 6). With these parameters, the observed and computed groundwater heads showed good compromise with a correlation coefficient of 0.8, Normalized Root Mean Square (NRMS) of 1.02 % and Root Means Square (RMS) of 3.7 m (Fig.7). The simulated groundwater seepage of 78133 Mm^3 is closely matching with observed groundwater seepage of 77760 Mm^3. The computed flow model was tested with observed groundwater heads of September 2008, and there is no significant change in RMS (3.4) and NRMS (1.1).Therefore, the model is considered reasonably calibrated. The computed groundwater contours indicated that predominant groundwater flow direction from NW to SE direction (Fig.7).

Groundwater Budget

After the calibration of groundwater flow model at reasonable level, the zone budget has been computed by assigning different zones along tunnel in the groundwater flow model using zone budget package. The computed groundwater budget indicated significant river leakage in the study area (Table 1). In the table 1, inflow indicates water flow into the aquifer from different sources and outflows represent water flows from the zones/aquifer to surrounding area. The computed groundwater seepage into the different parts of the Tunnel and location of the zones are shown in Figure 8. The computed zone budget indicated that Zone 4 and Zone 10 around the Tunnel between Dry Nala and Nilli khad stream receive high groundwater seepages of about 15650 m^3 and 20850 m^3 respectively. The model estimated that total groundwater seepage into the Tunnel is 78313 m^3. The computed groundwater seepage closely matches with the observed seepage of 77760 m^3. Then, the model was tested with a series of pumping wells along the Tunnel and observed that there is no significant reduction in the seepage or groundwater levels (Fig. 4). Further, the model was tested

with drain conditions. The drain conductance was doubled to the initial simulated value and it is observed that there is a significant reduction of groundwater level around the Tunnel. Therefore, it is understood that artificial increase of hydraulic conductivity or increase in conductance can drain out the seepage water. The lateral perforated subsurface drainage was suggested to increase the conductivity and to drain out the groundwater seepage for the protection and sustainable maintenance of the Tunnel.

Solution To Drain Out The Seepage Water

The groundwater seepage into the Tunnel, particularly during the monsoon period can be solved by enhanced innovated drainage system to drain out the seepage by gravity from the Tunnel (Li et al., 2009). To enhance the permeability in the model, the conductance of Tunnel was increased by two times (300 to 520 m^2/day) leading to drastic decrease in groundwater levels. In this context, horizontal perforated pipes with highly permeable geo-media around the pipes close to the invert level of tunnel are suggested to enhance the in situ permeability. The perforations can add additional value if it is aided by annular tube wells filled with highly permeable geo-media from ground surface to adjacent of invert level of the tunnel for the generation of quick drainage (Fig. 9a). The suggested perforated pipes will drain out the seepage water by free drainage through horizontal perforated annular pipes inserted at 40 - 60 cm above the invert level. The cross section of the perforated pipe is presented in Figure 9b.

Length Of Laterals

Let n be the number of lateral pipes with uniform intervals around the circumference of the caisson. Assuming 16% open area, 40% clogging of the slots and entrance velocity of 6mm/sec with 20 cm diameter, the total seepage can be calculated by

$$Q= (\Pi\ d\ N\ Ls\ P)\ Ve\ (Raghunath,\ 2005)$$

Where   P is the effective percent of open area
       Ve = entrance velocity
       Ls = Length of the lateral
       N = Number of laterals
       P = (0.16 * 0.60)
    Average seepage inside Tunnel is 900 l/sec = 3240 m^3/hr = 77760 m^3/day

$$\frac{77760}{24*60*60} = (\Pi * 0.20)\ N * 5m * (0.16 * 0.60) * 0.006$$

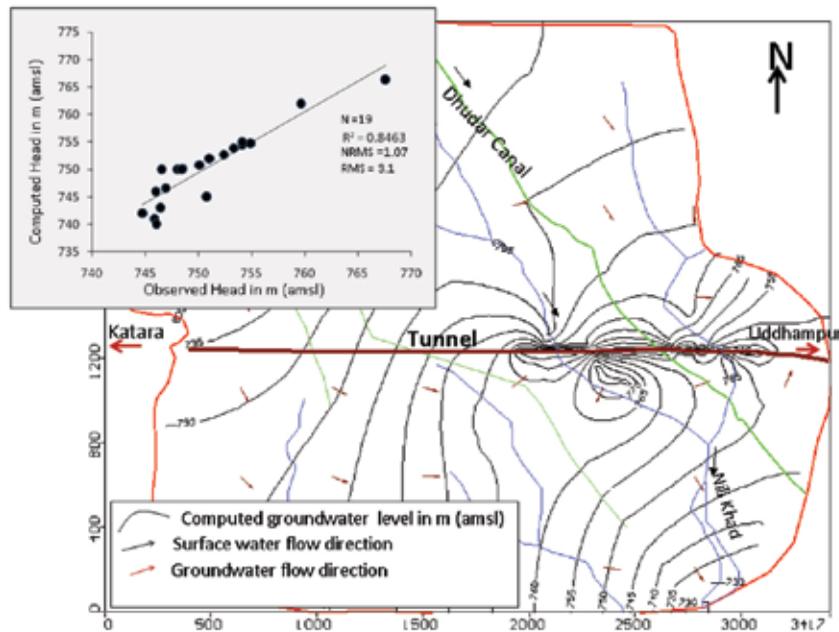$$0.9 = \frac{22}{7} * 0.2 * N * 5 * 0.096 * 0.006$$

Figure 7. Computed vs. observed groundwater heads, computed groundwater contours and velocity vectors in the flow model (X and Y axis are in m)
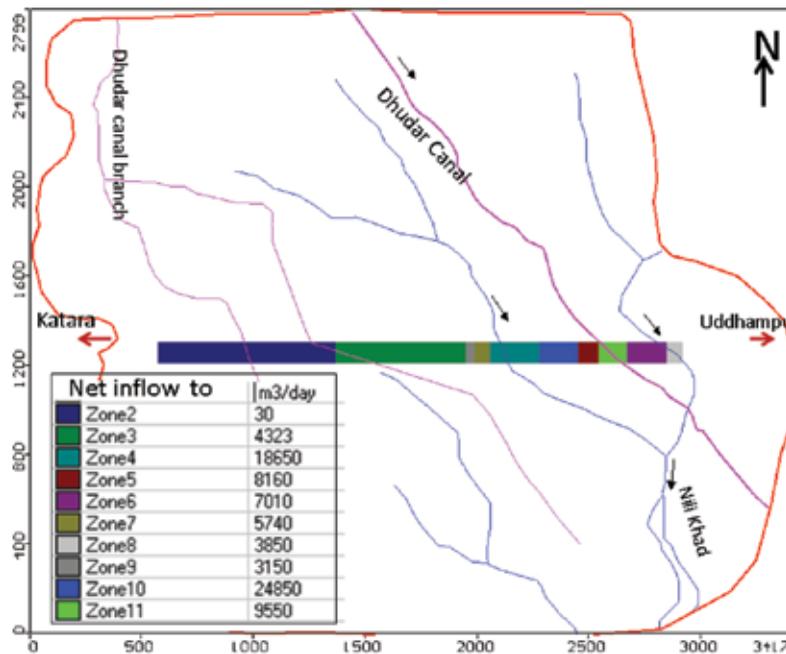

Figure 8. Location of the different zones for estimating the zone budget (X and Y axis are in m)

0.9 = 0.00180864 * N
Number of Laterals of 5 m length (N) = 497

It is proposed to drill 10 - 12 tube wells from ground surface up to the invert level adjacent to tunnel axis (4 - 5 m on the northern part). The bottom of the wells should touch the inserted perforated annular pipes filled with geo-media. Total length of 2500 m perforated pipes are required to drain out the total volume of 980 l/sec seepage water. The proposed length may be achieved through insertion of 500 pipes of 5 m in length at an interval of 2
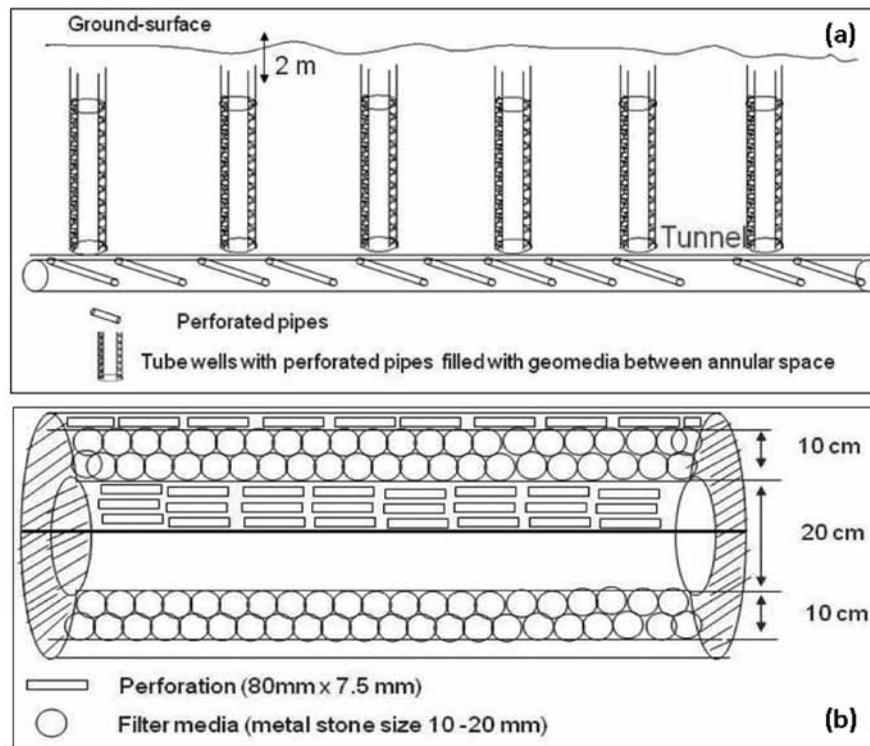
Figure 9. Perforated annular pipes, tube wells with geo media tunnel alignment (a) and cross section of the perforation of the pipe (b) for draining of the seepage water, Jammu and Kashmir (X and Y axis are in m)

m covering 1200 m length of seepage area in the Tunnel. The geo-media could be the gravel with 10 -15 mm size facilitated by enhancing vertical flows achieved by drilling 10 - 12 tube wells of 40 cm diameter with 10 cm annular space filled with geo-media. The post field visit in the year 2012 and enquiries with RITES indicated that the suggested technology successfully implemented in the area by RITES was able to drain out the seepage effectively, which facilitated hassle free movement of trains between Udhampur and Katara in the Jammu Kashmir.

CONCLUSIONS

The hydro geomorphological investigations revealed that the area is occupied by alluvial soils belonging to the Middle Shiwalik Group. Hydrogeological, geomorphological and lineament information was successfully deployed for subsurface conceptualization and aquifer parameterization in the groundwater flow model for the estimation of seepage into the Tunnel. In the eastern part of the Tunnel, more groundwater seepage has occurred due to the presence of palaeo channel and Dhudar canal. The seepage volume declined towards the Western end driven hydrogeologic environment. The model results revealed that the groundwater seepage into the tunnel could successfully be drained outby providing additional drainage facilities with perforated pipes embedded with permeable geo-media

in the subsurface. The combination of enhanced vertical permeability embedded with tube wells and perforated pipes of similar nature would help to drain the seepage water from the Tunnel by gravity.

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