Characterization of small-scale groundwater irrigation schemes in a humid coastal region of southern India

Sandeep Nayak[1]* and Lakshman Nandagiri[2]

[1]Department of Civil Engineering, Anjuman Engineering College, Bhatkal 581 320, Karnataka, India; [2]Department of Applied Mechanics and Hydraulics, National Institute of Technology, Surathkal, Mangalore 575 025, Karnataka, India.

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Abstract

Small-scale groundwater irrigation schemes involving large diameter wells are prevalent in the coastal district of Uttara Kannada, Karnataka State, India. A study was conducted to assess the characteristics of these large diameter open wells and the hydraulic properties of shallow aquifers. Field tests were conducted in 19 wells to assess their potential to supply irrigation water requirements of the region. Constant discharge pump tests indicated significant spatial variations in aquifer transmissivity (5.60 to 64.55 $m^2 \cdot day^{-1}$) and specific yield (0.063 to 0.95). Low transmissivity values signify poor potential of the aquifer to supply irrigation water needs. Exponential prediction models linking transmissivity and well specific capacity gave a good fit. Implications of spatial variability in aquifer parameters on irrigation development in the region are highlighted.

Keywords: Aquifer parameters, Large diameter wells, Pump tests.

Introduction

Small-scale irrigation schemes have significantly contributed to agricultural productivity in several parts of the world, especially in Asia (Campbell, 1995). Diversion or direct pumping from rivers and streams, gravity flows from small reservoirs (tanks), and pumping from the underlying groundwater aquifers constitute the principal means of sourcing water for these small-scale irrigation schemes. In Uttara Kannada district of Karnataka state in southern India, where 80% of the agricultural land holdings of 0.1495 million ha are small or medium in size (less than 10 ha; Agricultural Census, 2000–01), wells provide about 30% of the water sources for irrigation (Irrigation Report, 2001). Low cost of construction as well as ease of maintenance and operation make the large diameter open wells particularly attractive. In addition, such wells are also suitable for shallow aquifers with low transmissivity (Rushton and Holt, 1981). However, with increasing competition for water from the domestic and industrial sectors and also overexploitation of the ground water resources, the small-scale irrigation systems in coastal Karnataka are facing serious threats (Nayak, 2008).

In spite of the popularity of large diameter open wells for supplying irrigation water needs of small-scale irrigation systems in the western coast of India, few scientific studies have elucidated their hydraulic characteristics. Clearly, the economic efficiency of agricultural productivity in smallholder production systems is linked to hydraulic efficiency of the wells and their ability to provide critical crop water requirements during the dry season (Prastowo et al., 2007). Hydraulic characteristics of the underlying aquifer, drawdown behavior under continuous pumping, specific capacity of the well, radius of influence and interference effects, and well efficiency are major determinants in this respect. The present study was

*Author for correspondence: Phone +918258 262713, Fax +918258 262723; Email <sandeejn@yahoo.co.in>.

taken up with the objective of evaluating the hydraulic properties of the shallow aquifer and the characteristics of large diameter open wells in the Uttara Kannada district, Karnataka state, India. Field tests were conducted to understand the regional aquifer properties and the characteristics of wells, besides making efforts to develop a model for estimating aquifer transmissivity (*T*) based on well specific capacity (*SC*).

Materials and Methods

Site description

Uttara Kannada is located on the western coast of India adjoining the Arabian Sea. The region experiences humid tropical climate with a wet season extending over four months (June to September) when significant rainfall (on an average 3500 mm annually) occurs due to the Indian south-west monsoon phenomenon. This is, however, followed by a long dry period extending from October to May. Physiographically, the region comprises of the steep hills of Sahayadri Mountains (Western Ghats) to the east, a mid-land region with undulating topography, and the coastal plains. Geologically, it is characterized by the extensive occurrence of highly weathered laterites and lateritic soils overlying granitic gneisses. Major arable crops include paddy, pulses, and groundnut in the midlands and plains, while plantation crops such as arecanut, coconut, banana, and cacao are predominant in the hilly areas. Although most of these crops are rainfed, irrigation is essential during the dry months. Groundwater, which mostly occurs under unconfined conditions, is used extensively for this purpose. There are a total of 13132 wells in the district, of which 9811 are non-energized open wells (Irrigation Report, 2001). Despite significant groundwater recharge that occurs during the rainy season, groundwater discharges to the sea and surface water bodies often deplete it.

Characterizing hydraulic properties

Hydraulic properties of the aquifers and associated layers were determined by pumping test, as described by Todd (1995). It involved abstraction of water from a well at a controlled rate and observing its drawdown. Pumping and recovery data for 19 open wells, i.e., 14 circular and five rectangular (H5, K3, K4, K7, and K8), in the three *taluks* of Uttara Kannada district were recorded during the period from October 2002 to March 2003. Specific locations of the wells are shown in Fig. 1 (13°59’20” to 14°28’20” N latitude and between 74°23’42” and 74°32’50”42 E longitude). Radius of the wells in the study area ranged from 0.85 to 3.0 m and depth from 2.1 to 13 m. In all cases, pumping duration was not less than 262 min. *SC* for each of the 19 wells was computed as the ratio of constant discharge at which the pumping test was conducted to the maximum observed drawdown in the pumped well. Given the sandy-gravel nature of the study aquifer, radius of influence (*R*) was conservatively assumed as 150 m.

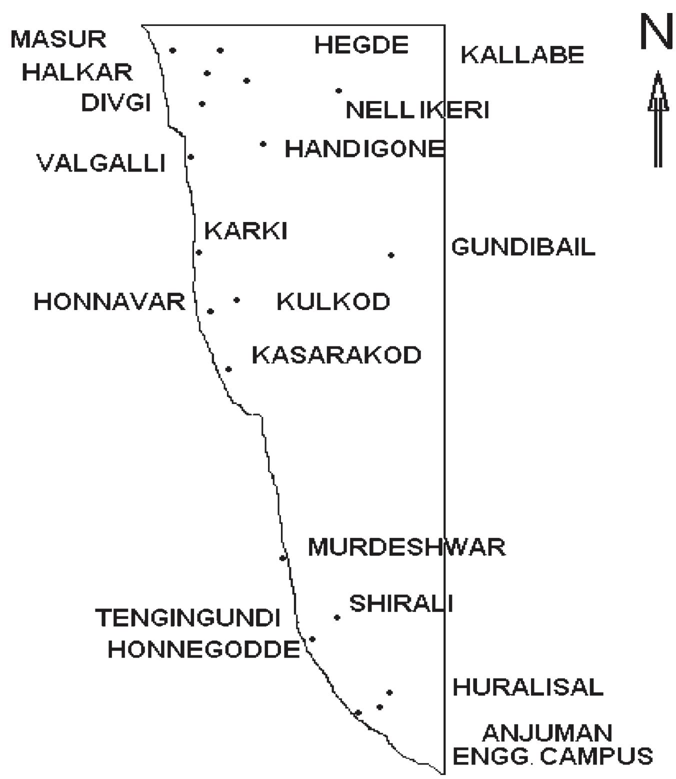


Figure 1. Map of the coastal region of Uttara Kannada district in Karnataka showing locations of the pumped wells.

Transmissivity indicates how much water will move through the formation and storage coefficient, a dimensionless parameter, indicates how much can be removed by pumping or draining. The storage coefficient for an unconfined aquifer corresponds to its specific yield (S)— ratio of the volume of water that after saturation can be drained by gravity to its own volume (Todd, 1995). In order to determine T and S, the drawdowns in a pumped well and in installed observation wells were recorded at different time intervals. If observation wells were not available, the records were taken in the pumped well and plotted as log S versus log T (Aziz, 1987). Tests were conducted during the pre-monsoon period of 2002. AquiferWin32® software, which incorporates the Neuman approach (Environmental Simulations International, 2000), was used to analyze the pump test data and for determining T and S.

Data on T and SC from 14 of the 18 wells were used to develop regression models following the least-squares method and data from the four remaining wells were used for model validation. Well H-1 was treated as an outlier since SC for this well was significantly higher (2073.6 $m^2 \cdot day^{-1}$) than the values obtained for the remaining wells. Coefficient of determination (R^2) and root mean squared error ($RMSE$) during calibration and validation were used to evaluate the model performance.

Results and Discussion

The observed time-drawdown behavior for well B-1 is given in Fig. 2. The time-drawdown responses were similar for all wells and were significant in the pumped wells in most places. As can be seen from Figs. 3 and 4, the data points matched with the type curves given by Neuman (1975). Analysis of the pumping test data

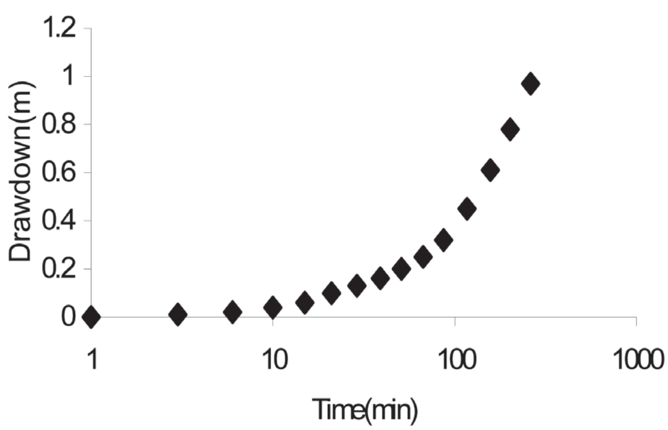
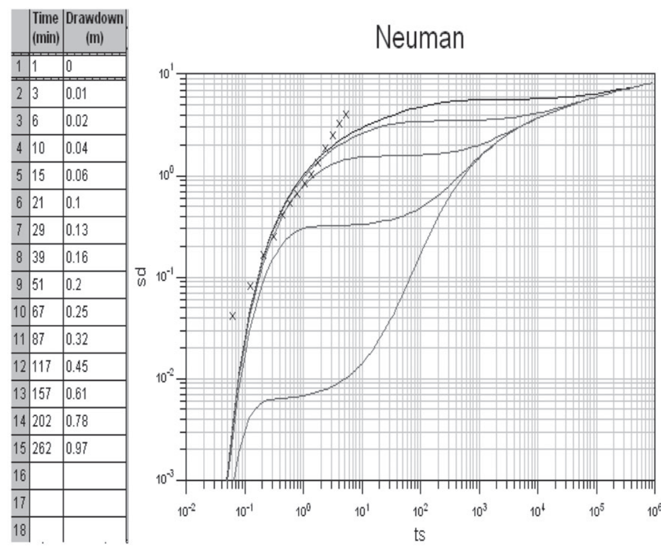


Figure 2: Observed drawdown versus time at well no. B-1, Engineering College location, Uttara Kannada, Karnataka.

from unconfined aquifers show that drawdowns varied at different rates from those predicted by the traditional Theis equation (see Jacob, 1940). When these drawdowns were plotted against time on logarithmic paper, it gave an S-shaped curve consisting of a steep segment at early times, a flat segment at intermediate times, and a somewhat steeper segment at later times (Fig. 3). The physical phenomenon that causes this behavior is known as delayed yield, delayed drainage, or delayed gravity response. The delayed yield could be simulated mathematically by using the constant values of specific storage and specific yield, considering the unconfined aquifer as a compressible system (Boulton and Pontin, 1971).



	Time (min)	Drawdown (m)
1	1	0
2	3	0.01
3	6	0.02
4	10	0.04
5	15	0.06
6	21	0.1
7	29	0.13
8	39	0.16
9	51	0.2
10	67	0.25
11	87	0.32
12	117	0.45
13	157	0.61
14	202	0.78
15	262	0.97
16		
17		
18		

Figure 3. Matching of data points at A.E.C, Bhatkal, Uttara Kannada, Karnataka.

Spatial variability in aquifer parameters

Aquifer parameters (T and S) obtained using Neuman (1975) method for all 19 wells are shown in Table 1. T values ranged from 5.60 to 64.55 $m^2 \cdot day^{-1}$ and it was higher in the southern (wells B1 and B5) and western regions (wells H1 and K4), compared to the northern region (wells K1, K5, and K6) of coastal Uttara Kannada district. Since T is indicative of the rate of groundwater flow to a well, a high value for this parameter is desirable from the viewpoint of groundwater development. According to Driscoll (1987), T greater than 124 $m^2 \cdot day^{-1}$ may be adequate. However, Prastowo et al. (2007) argued that an aquifer

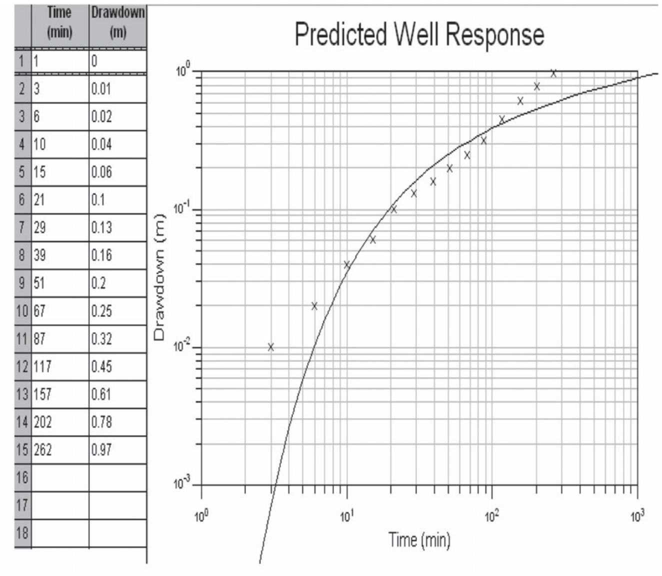


Figure 4. Well response for the well at A.E.C at Bhatkal, Uttara Kannada, Karnataka.

may be classified as *low class* if T is less than 300 $m^2 \cdot day^{-1}$ and *high class* only if T is greater than 1000 $m^2 \cdot day^{-1}$.

Wells located at Shirali (B5), Kasarkod (H1) and Karki (H2) showed higher specific yields indicating that these wells may permit substantial release of water. Higher values of S obtained in this study also indicate that the aquifer might be mainly comprised of sand or gravel, or their mixture. *SC* values ranged from 14.58 to 2073.6 $m^2 \cdot day^{-1}$ (Table 1). Overall, it appears that most of the wells tested in this study were productive (high specific capacity) and possessed high specific yield (average value of 0.27). Therefore, field crops such as pulses and groundnut in the plains and plantation crops such as arecanut, coconut, and banana in the hilly terrain can be irrigated during dry periods from these groundwater resources without problem. However, from the low aquifer transmissivity values obtained, it appears that the potential of the aquifer to sustain further increase in water withdrawals is limited.

The area of well influence (AWI) for the study site was 7 ha, considering R as 150 m. Prastowo et al. (2007) suggested that AWI can be approximated as the potential irrigated command area of the well. Given that the

Table 1. Aquifer parameters for pumped wells in the coastal district of Uttara Kannada, Karnataka, India, obtained from Neuman (1975) method during the period from October 2002 to March 2003.

Location	Specific capacity ($m^2 \cdot day^{-1}$)	Transmissivity ($m^2 \cdot day^{-1}$)	Specific yield
B1–Engineering College	133.60	41.56	0.162
B2–Tengingundi	55.74	13.84	0.187
B3–Huralisal	43.20	9.93	0.146
B4–Honnegadde	134.64	25.27	0.253
B5–Shirali	737.28	64.55	0.956
B6–Murdeshwar	96.00	22.23	0.084
H1–Kasarkod	2073.60	56.73	0.638
H2–Karki	169.79	28.19	0.581
H3–Honnavar Town	21.60	6.47	0.327
H4–Gundibail	192.00	43.19	0.038
H5–Kulkod	172.80	60.98	0.154
K1–Nellikeri	24.04	9.47	0.159
K2–Halkar	14.58	5.6	0.127
K3–Kallabbe	469.56	58.98	0.313
K4–Divgi	233.51	56.08	0.375
K5–Hegde	42.63	10.61	0.219
K6–Handigone	68.57	10.92	0.227
K7–Valagalli	86.40	24.89	0.108
K8–Masur	64.00	22.74	0.063

irrigated area in the three coastal *taluks* of Uttara Kannada district is 8312 ha, approximately 30% of this area is served by groundwater wells (Irrigation Report, 2001), and that there exists 11795 wells in this region, the average irrigated command area (ICA) per well is 0.22 ha. The ratio of AWI to ICA works out to 32, which is far greater than unity and therefore is indicative of the extremely dense network of groundwater wells. Implicit in this is that interference of wells within radius of influence of wells is likely and it may affect well performance either due to a reduction in transmissivity following a lowering of the groundwater level or due to an increase in well loss associated with clogging or deterioration of the well screen.

Transmissivity vs. specific capacity relationships

Exponential and log functions linking T and SC were developed as given in Table 2. As can be seen from this table, the exponential model (Eq. 1) gave a better fit: higher coefficient of determination (R^2) and lower *RMSE*. The calibration performance of Eq. 1 (Fig. 5) also highlights its utility as a prediction model for aquifer transmissivity based on well specific capacity. Fig. 6 compares the observed values of transmissivity with those estimated by the calibrated form of the model (Eq. 1) for the four wells included in the validation set. It indicates that the estimated transmissivity values in the validation phase are slightly lower than the observed ones.

Conclusions

Our findings, despite its limited duration, are critically important in the context of further development of groundwater resources for irrigation in the coastal region of Uttara Kannada district. Although small wells

Table 2. Performance statistics for regression models relating T and SC for 14 wells in the coastal region of Uttara Kannada district, Karnataka.

Equation	Model	Calibration		Validation	
		R^2	*RMSE*	R^2	*RMSE*
1	T=0.862* $SC^{0.7067}$	0.855	12.35	0.990	8.60
2	T=18.442 $ln\ SC$ – 55.567	0.832	29.59	0.823	26.45

T. Transmissivity; SC. Specific Capacity; R^2. Coefficient of determination; *RMSE*. Root mean squared error.

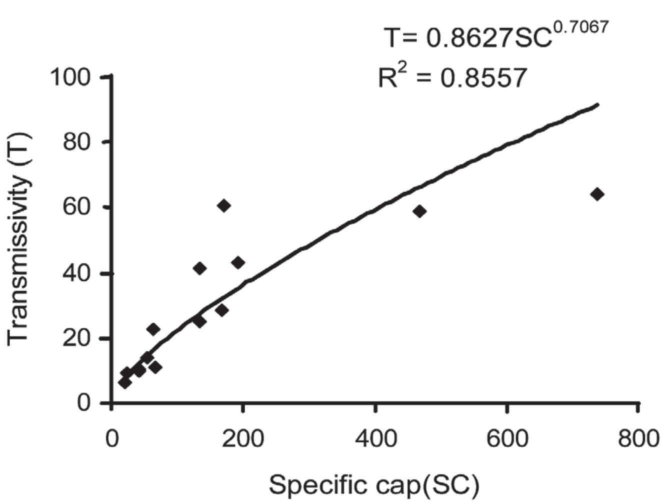


Figure 5. Relation between Transmissivity (T) and Specific Capacity (SC), Uttara Kannada, Karnataka.

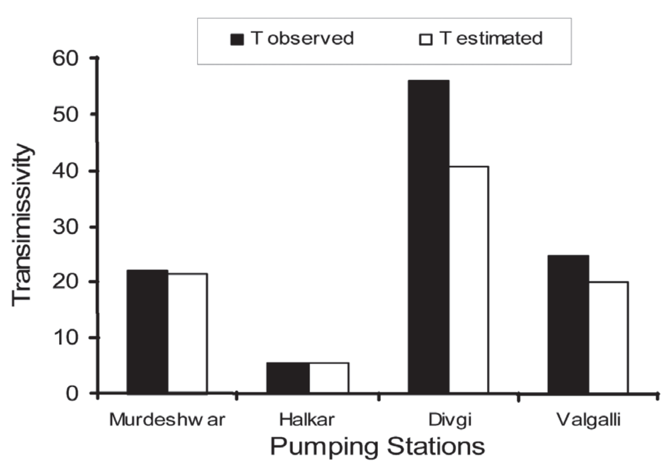


Figure 6. Observed and estimated values of aquifer transmissivity (T) in the validation phase of wells in Uttara Kannada, Karnataka.

in an aquifer possessing low *T* may perform reasonably well for the small farmer, further increase in density of such wells will certainly depress yield per well. This may lead to a situation where farmers may either lower the pumps deeper into the wells or may even use higher capacity pumps/motors. Non-energized wells also are likely to be energized in an effort to increase productivity. In either case, the dry season supplies from the individual wells may become unreliable and groundwater extraction would become more expensive. In addition, questions relating to the characteristics of the groundwater aquifer and efficiency with which water can be withdrawn using shallow, large dimension wells over sustained periods need to be answered. Under increasing levels of extraction, sustainability of small-scale groundwater irrigation schemes in the coastal region of Uttara Kannada district, therefore, cannot be ensured. This is mainly because of the inability of the underlying unconfined aquifer to support large water withdrawals, which calls for regulations to prevent indiscriminate development of groundwater resources. Our results also indicate significant spatial variations in aquifer parameters in the study region. Moreover, the low aquifer transmissivity values indicate that the potential of the aquifer to sustain further increase in water withdrawals is limited. Further studies are necessary to gain a more detailed understanding of regional groundwater flow and sustainable aquifer yield.

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