Hydrological-drainage analysis in watershed-programme planning: a case from the Deccan basalt, India

Vijay Pakhmode · Himanshu Kulkarni · S. B. Deolankar

Abstract Watershed development in India is being adopted increasingly as an integrated mechanism of addressing ecological concerns, particularly in dryland areas. Increasing groundwater recharge constitutes one of the principal objectives of watershed-development programmes because many parts of India face acute shortages of groundwater resources on which rural livelihood depends. A combination of hydrogeological mapping and drainage analysis can form an important tool for planning of watershed-development programmes. Studies on the Kurzadi watershed from the Deccan volcanic province in west-central India illustrate how this technique is useful in selecting sites for artificial recharge of groundwater.

The Kurzadi river basin includes three third-order sub-basins that are compared for relative variability in surface-material permeability. Domains of high surface permeability typically indicate relatively higher length ratios and lower drainage density and stream frequency. In the Kurzadi watershed, drainage parameters reveal areas for recharge-related measures and areas where surface-water augmentation measures can be undertaken, even on lower, second-order streams.

Résumé En Inde, la mise en valeur de bassins versants est en train d'être pris en compte de plus en plus comme un mécanisme intégrateur de problèmes concernant l'écologie, en particulier dans les régions sèches. L'accroissement de la recharge des nappes constitue l'un des principaux objectifs des programmes de mise en valeur des bassins versants, parce que de nombreuses régions de l'Inde doivent faire face à une grave pénurie de ressources en eau souterraine, dont dépendent les moyens d'existence en zones rurales. Une combinaison de cartographie hydrogéologique et d'analyse du drainage peut constituer un outil important de planification des programmes de développement des bassins. Des études sur le bassin de Kurzadi, dans la province volcanique du Deccan, dans le centre-ouest de l'Inde, illustre combien cette technique est utile pour décider des sites de recharge artificielle de nappe.

Le bassin de la rivière Kurzadi est formé de trois sous-bassins de troisième ordre dont on a comparé la variabilité relative de la perméabilité de surface. Des domaines de forte perméabilité de surface dénotent bien des rapports de longueurs relativement plus forts et une densité de drainage et une fréquence de cours d'eau plus faibles. Dans le bassin de la rivière Kurzadi, les paramètres du drainage révèlent des zones convenant à des mesures relatives à la recharge et des zones où des mesures d'augmentation de l'eau de surface peuvent être entreprises, même sur des cours d'eau plus petits, de second ordre.

Resumen En la India, se está adoptando el desarrollo de cuenca de forma creciente como un mecanismo integrado para abordar las inquietudes ecológicas, particularmente en zonas áridas. El aumento de la recarga a los acuíferos constituye uno de los objetivos principales de los programas de desarrollo de cuenca, porque muchas zonas de la India deben afrontar períodos acusados de escasez de recursos de aguas subterráneas, de los que dependen los asentamientos rurales. La combinación de cartografía hidrogeológico y de análisis del drenaje puede significar una herramienta importante para la planificación de los programas de desarrollo de cuenca. Los estudios efectuados en la cuenca de Kurzadi, en la Provincia Volcánica de Deccan (región central-occidental de India) ilustran la utilidad de esta técnica con el objeto de seleccionar emplazamientos adecuados para la recarga artificial de acuíferos.

La cuenca del río Kurzidi incluye tres subcuencas de tercer orden que han sido comparadas con respecto a la variabilidad relativa de la permeabilidad en superficie.

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Los dominios de alta permeabilidad superficial son indicadores típicos de relaciones de longitud relativamente mayores y de menor densidad de drenaje y frecuencia de curso fluvial. En la cuenca de Kurzadi, los parámetros de drenaje revelan áreas de medidas relacionadas con la recarga y áreas en las que se puede emprender medidas de aumento de agua superficial, incluso en cursos fluviales menores, de segundo orden.

Keywords Hydrological-drainage analysis · Watershed-programme planning · Deccan basalt · India

Introduction

Land-use intensification and population growth in India have resulted in the increasing use of groundwater for various activities. The increase in water use has affected both surface and groundwater supplies with many areas of the country clearly showing signs of acute water crisis. Many zones of low and erratic rainfall in India are often underlain by hard rocks. Hard rocks generally include volcanic and crystalline rocks wherein the permeability is low and infiltration is restricted to the weathered and fractured zones. Such hard-rock areas are always prone to frequent water crises because of the low porosity of hard-rock aquifers, compounded by uncertain rainfall. An increasingly popular means of addressing water-management problems in such areas is known locally as ‘watershed development’.

One of the basic objectives of any watershed-development programme is to increase recharge. However, the approach to identifying sites that are conducive to recharge is often so broad-based, that it results in poor siting. For example, topography is the only physical feature considered in the selection of most recharge sites. Groundwater storage, its movement and recharge are absolutely dependent on the hydrogeological characteristics of the host rock or, in other words, these features comprise the physical system of the watershed. The control parameters for a watershed as a physical system are geological, geomorphological, hydrological and hydrogeological in nature. These parameters are often neglected or are only considered marginally during the planning and execution of watershed development programmes (Kulkarni 1998).

Hydrogeological studies hold immense potential in the planning and execution of ‘measures’ in watershed-development programmes. Siting of facilities for enhancing recharge is of great importance when planning a watershed-development programme. It is important to look into the hydrogeological configuration of a watershed so that recharge measures are put in the right perspective at the planning stage itself. Hydrogeological mapping and morphometric drainage analysis can be integrated fruitfully to effectively plan the location of such facilities. A simple approach involving a combination of hydrogeological mapping and watershed-drainage analysis is a useful tool in developing a ‘broad-based’ plan that is both practical and effective for siting of recharge and water-harvesting facilities.

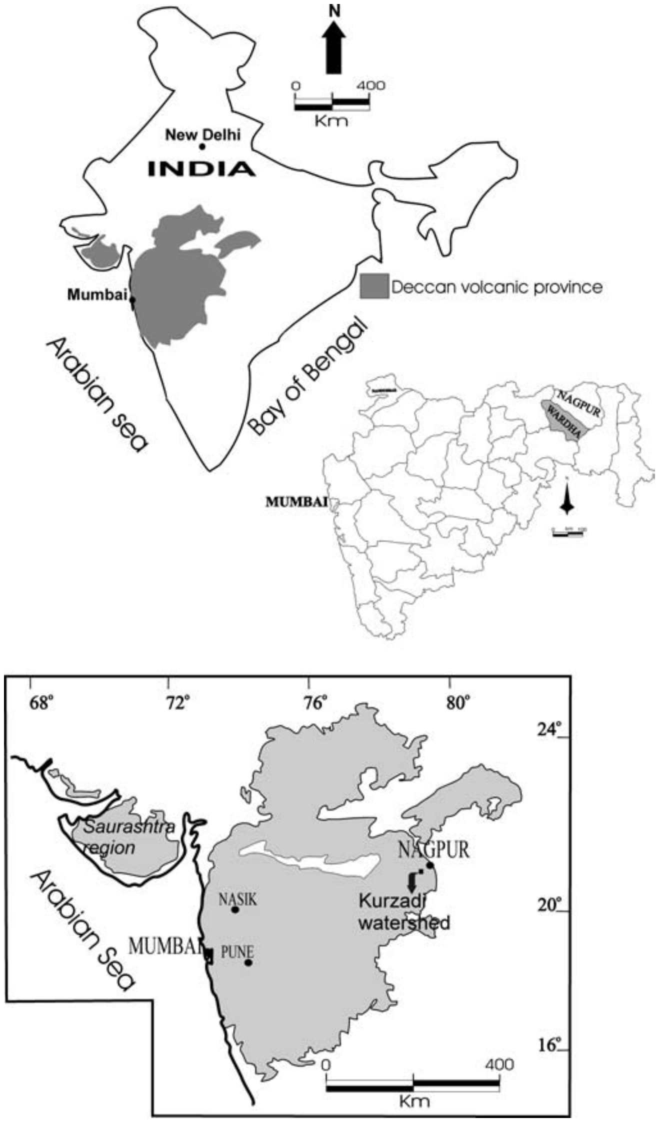

Fig. 1 Regional location map of Kurzadi watershed, and map showing the extent of the Deccan volcanic province in west-central India. Wardha district is indicated in the districts outline map of Maharashtra state, as an additional reference

A study to illustrate this approach is presented here that examines a typical watershed in the Deccan volcanic province largely encompassing Deccan basalt lava flows. Located in central India, the watershed represents an area of 19.08 km^2 comprising the village of Kurzadi in Wardha tehsil of Wardha district in Maharashtra, shown in Figs. 1 and 2. A tehsil is a subdivision of a district which itself is the basic unit of subdivision of a state. A tehsil is usually a small township and forms the administrative headquarters of a cluster of several villages.

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Hydrogeological Setting

A base map on the scale of 1:10,000 was first prepared using the Survey of India topographic sheets numbered 55 L/5 and 55 L/6. In order to map the Deccan basaltic-flow units from the Kurzadi watershed the methodology proposed by Kulkarni and Deolankar (1989, 1995) and Kulkarni et al. (2000) was adopted, wherein the layered sequence of Deccan basalts is classified into amygdaloidal basalts and compact basalts. The amygdaloidal basalts and compact basalts alternate with each other in a vertical sequence of lava units. The distribution of these basalts within the Kurzadi watershed was mapped in the field. The resulting hydrogeological map (Fig. 2) was prepared after studying the surface geology and analysing the data collected from a detailed inventory of dug wells.

Amygdaloidal basalts in Kurzadi watershed are quite heterogeneous and coarse grained and they are capped by a red tuffaceous horizon (commonly referred to as ‘red bole’). They are sheet-jointed horizontally and interconnected vertically, thus facilitating the storage and movement of groundwater. Sheet joints develop by the unloading of overburden from the top (Ollier 1976) and the jointing may be enhanced further by the action of circulating groundwaters (Kulkarni and Deolankar 1995).

Compact basalts in the Kurzadi watershed, on the other hand, are fine grained and homogeneous. Fractures are mostly vertical and not as open as the sheet joints in the amygdaloidal basalts. Sub-vertical fractures are prolific in the upper portion of the compact basalt but their frequency and apertures reduce with depth, the rock grading downwards eventually into a very compact, fine-grained basalt. Such fractures are capable of storing only limited amounts of groundwater.

There are five distinct basalt units within the Kurzadi watershed; two are amygdaloidal basalts (VAB-1 and 2) and three are compact basalts (CB-1, 2 and 3). Groundwater in the Kurzadi watershed is almost entirely obtained through large-diameter open wells. Most dug wells in the watershed are located within CB-1, VAB-1 and CB-2 that underlie the lower reaches of the watershed, although some dug wells have also been constructed in the upper basalt units (i.e. VAB-2 and CB-3). Dug wells are typically 10 to 12 m deep, although there are a few deeper wells, especially in the upper and middle reaches. Well diameters range between 2 and 10 m. Except for some five drinking-water wells, all the other dug wells are used for irrigation. The sheet joints of the amygdaloidal basalt units, where they occur between compact basalt units, together with the joints of the compact basalt unit, act as the ‘inflow zones’ (Kulkarni and Deolankar 1997) into the well and account for the permeability of these basalt aquifers.

Groundwater-discharge areas are characterised by shallow water tables of ≤ 1 m bgl (Davis and Dewiest 1966; Fetter 1980). Such discharge areas have been identified in the Kurzadi watershed where the flow is measurable by a portable V-notch at the contact of the basalt-flow unit VAB-1 and the underlying flow unit CB-1. This contribution of groundwater to the base flow from the stream banks is manifested by the natural groundwater gradient towards the stream and the shallow water levels in the wells nearby, all within 2 m of ground level, even during summer.

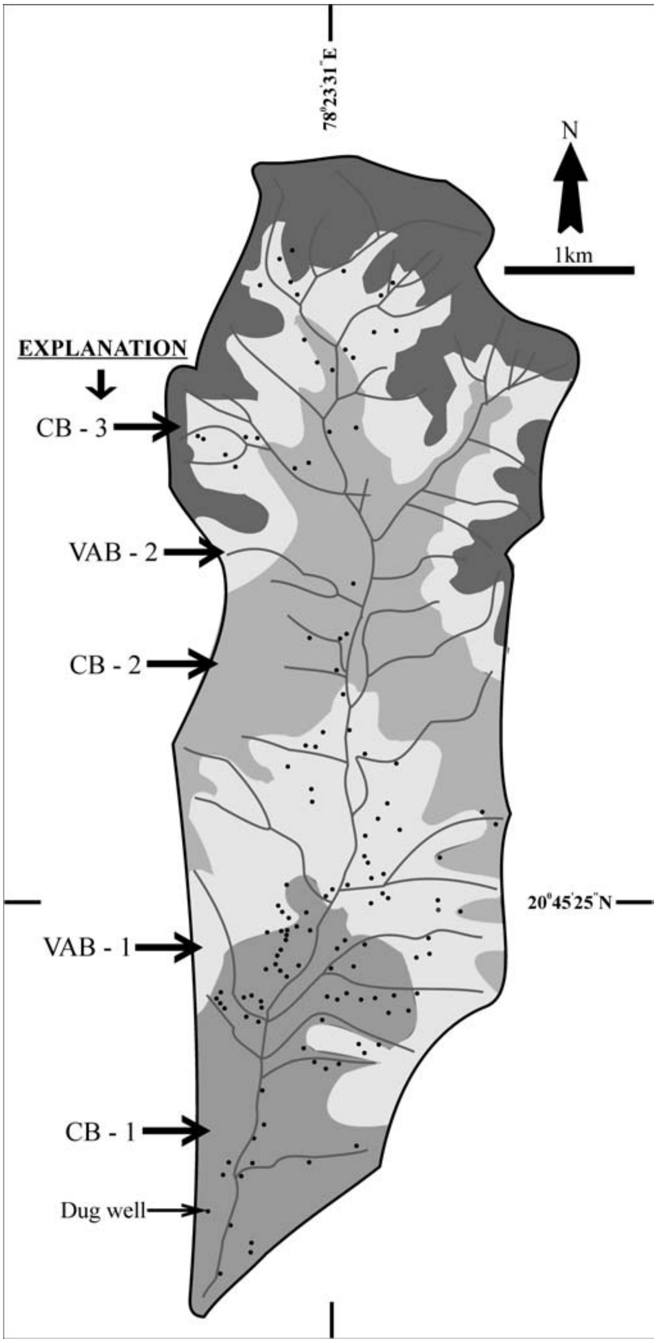

Fig. 2 Hydrogeological map of the Kurzadi watershed showing distribution of dug wells and disposition of vesicular-amygdaloidal basalt units (*VAB*) and compact basalt units (*CB*)

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Drainage Analysis

Evaluation of the characteristics of the drainage network of a basin using quantitative morphometric analysis can give information about the hydrological nature of the rocks exposed within the drainage basin. A drainage map of a basin provides a reliable index of the permeability of the rocks and also gives an indication of the yield of the basin (Wisler and Brater 1959). The yield of a basin is the flow per unit area and normally includes surface-water flows unless mentioned otherwise. Normally, such an analysis of drainage basins involves the evaluation of drainage parameters such as bifurcation ratio, length ratio, drainage density, constant of channel maintenance, length of overland flow and stream frequency. Hydrogeological observations, integrated with drainage analysis, provide useful clues regarding broad relationships among the geological framework of a watershed, surface flow and the recharge.

Figure 3 is a drainage map of the Kurzadi watershed, prepared from the Survey of India topographic sheets numbered 55 L/5 and 55 L/6. This drainage map was analysed by making two types of measurements, linear-scale measurements and dimensionless numbers. The linear-scale measurements are the length of the stream channel of a given order, drainage density and constant of channel maintenance, and the dimensionless numbers are usually the ratios of these length measures. The Kurzadi basin was analysed for stream-order analysis, bifurcation ratio (R_b), length ratio (R_l), drainage density (D_d), constant of channel maintenance ($1/D_d$), length of overland flow (L_g) and stream frequency (F).

Stream-Order Analysis

The advantage of ordering streams is that the stream order is a dimensionless number and hence can be used for the comparison of geometry of drainage network on different linear scales. A very common dilemma in watershed-development projects is the comparison of maps of different types, ranging from regional topographic sheets to local revenue maps or cadastral maps. Although it is somewhat difficult to generate thematic maps from such a

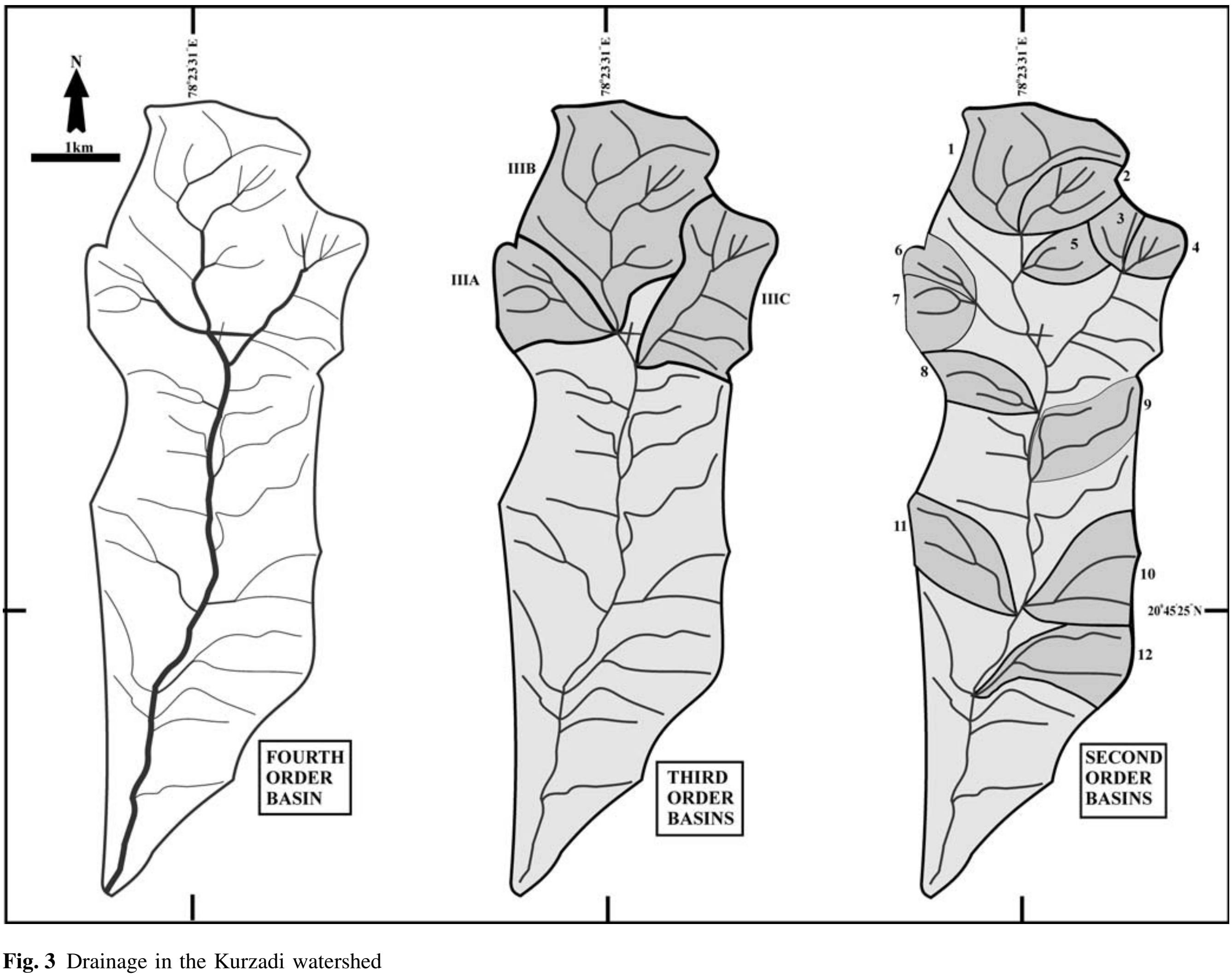

Fig. 3 Drainage in the Kurzadi watershed

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set of diversely scaled base maps, drainage mapping is the easiest and a drainage map is often the first real map that is generated in a watershed-development project.

The study area encompasses a fourth-order drainage basin, a part of the Yashoda River, which flows through the Kurzadi village. The Kurzadi basin drainage network was classified into orders according to the number of bifurcations using the method given by Strahler (1952). In this method, the smallest finger-tip tributaries are designated as first-order streams and two first-order streams unite to form a second-order stream; when two second-order streams join together a third-order stream is formed, and so on. The trunk or main stream through which all the discharge of water is carried is the stream of the highest order. The details of the order analysis of the Kurzadi basin are given below:

– First-order streams: 44
– Second-order streams: 12
– Third-order streams: 3
– Fourth-order streams: 1

Figure 3 highlights the catchment areas of the different orders of streams, beginning with the second-order streams. The details of the basins of the different orders are as follows:

– Number of second-order basins: 12 (designated as 1, 2, 3, ..., 12)
– Number of third-order basins: 3 (designated as III A, III B and III C)
– -Number of fourth-order basins: 1

Bifurcation Ratio (R_b)

In a sub-dendritic to dendritic drainage pattern, typical of the Deccan basaltic province, the number of streams of any given order is higher than the number of streams of the next higher order. The ratio of the number of streams of a given order to the number of streams of the next higher order, called the bifurcation ratio (R_b), reflects the complexity and degree of dissection of a drainage basin. The bifurcation ratios calculated for the third- and the fourth-order basins and the drainage characteristics of the Kurzadi watershed are given in Tables 1 and 2 and the bifurcation ratios of the second-order basins are given in Table 3. A bifurcation ratio greater than 5 indicates structurally controlled development of the drainage network (Strahler 1957).

It can be seen from Table 1 that the average bifurcation ratio for the fourth-order Kurzadi basin is 3.56, indicating that structural control on the development of the drainage is not as pronounced as the geomorphic control. It can be

Table 1 Drainage characteristics of the fourth- and third-order basins of the Kurzadi watershed

Basin	Order of streams	Total no. of streams	Bifurcation ratio (R_b)	Total stream length (km)	Average stream length (km)	Length ratio (R_L)
IV	1	44	3.67	34.85	0.79	-
	2	12	4.00	5.15	0.43	0.54
	3	3	3.00	3.2	1.07	2.49
	4	1	-	6.75	6.75	6.33
	-		Avg.=3.56	-		Avg.=3.12
III A	1	4	2.00	2.00	0.50	-
	2	2	2.00	0.50	0.25	0.50
	3	1	-	0.70	0.70	2.80
	-		Avg.=2.00	-		Avg.=1.60
III B	1	11	3.67	7.20	0.65	-
	2	3	3.00	2.10	0.70	1.08
	3	1	-	1.20	1.20	1.71
	-		Avg.=3.34	-		Avg.=1.40
III C	1	8	4.00	4.70	0.59	-
	2	2	2.00	0.40	0.20	0.34
	3	1	-	1.30	1.30	6.50
	-		Avg.=3.00	-		Avg.=3.42

Table 2 Drainage characteristics of fourth- and third-order basins of the Kurzadi watershed

Basin	Order of basin	No. of streams N	Basin area A (km^2)	Total length of streams L (km)	Drainage density D_d=L/A (km/km^2)	Constant of channel maintenance C=1/D_d (km^2/km)	Stream frequency F=N/A (per km^2)	Length of overland flow L_g=1/2D_d (km^2/km)
IV	4	60	19.08	49.95	2.62	0.38	3.14	0.19
III A	3	7	0.81	3.20	3.95	0.25	8.64	0.13
III B	3	15	3.69	10.50	2.85	0.35	4.07	0.18
III C	3	11	1.99	6.40	3.22	0.31	5.53	0.16

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Table 3 Drainage characteristics of the second-order basins of the Kurzadi watershed—Part I

Basin	Order of streams	Total no. of streams	Bifurcation ratio (R_b)	Total stream length (km)	Average stream length (km)	Length ratio (R_L)
1	1	4	4.00	3.25	0.81	-
	2	1	-	1.25	1.25	1.54
2	1	4	4.00	1.95	0.49	-
	2	1	-	0.70	0.70	1.43
3	1	2	2.00	1.05	0.53	-
	2	1	-	0.20	0.20	0.38
4	1	3	3.00	1.40	0.47	-
	2	1	-	0.20	0.20	0.43
5	1	2	2.00	0.95	0.48	-
	2	1	-	0.15	0.15	0.31
6	1	2	2.00	0.95	0.48	-
	2	1	-	0.30	0.30	0.63
7	1	2	2.00	1.05	0.53	-
	2	1	-	0.20	0.20	0.38
8	1	2	2.00	1.60	0.80	-
	2	1	-	0.20	0.20	0.25
9	1	2	2.00	2.50	1.25	-
	2	1	-	0.25	0.25	0.20
10	1	2	2.00	2.00	1.00	-
	2	1	-	0.30	0.30	0.30
11	1	2	2.00	1.55	0.78	-
	2	1	-	0.85	0.85	1.09
12	1	2	2.00	2.90	1.45	-
	2	1	-	0.55	0.55	0.38

seen from Table 1 that the average bifurcation ratios for the third-order basins III A, III B and III C are less than 5. Here too, for all three basins, the bifurcation ratios for the second- to the third-order streams are 2, 3 and 2 respectively, which indicates absence of any structural control on the development of the drainage network.

The bifurcation-ratio analyses for the second-order basins are given in Table 3. In the case of all these basins, the bifurcation ratios of first- to second-order streams are less than 4, which again indicates the general absence of significant structural control on the development of the drainage.

Length Ratio (R_l)

The length of a stream is a measure of the hydrological characteristics of the underlying rock surfaces and the degree of drainage. Wherever the formations are permeable, only a small number of relatively longer streams are formed; in a well-drained basin, a large number of streams of smaller length are developed where the formations are less permeable. The mean length of a stream of any given order is always greater than the mean length of a stream of the next lower order and, based on this, Horton (1945) proposed the factor length ratio (R_l), which is the ratio of the mean length of a stream of any given order to the mean length of a stream of the next lower order. The length ratio gives a general idea about the relative permeability of the rock formations in a basin. More specifically, it indicates if there is a major change in the hydrological characteristics of the underlying rock surfaces over areas of consecutive stream orders.

The average length ratio for the fourth-order Kurzadi basin is 3.12 (Table 1). However, the length ratio for the fourth-order stream within the Kurzadi basin is quite high (6.33). This indicates that the rock formations in the areas drained by the fourth-order stream are gentler in slope and/or more permeable than the rock surfaces under the lower order streams. A major length of the fourth-order channel flows over the VAB-1, which is likely to have permeable surfaces along this length. Sheet-jointed exposures of VAB-1, particularly in well sections, also support this hypothesis. VAB-1 is sheet-jointed prolifically in the area through which the fourth-order stream flows. The average length ratios for the third-order basins III A, III B and III C are 1.60, 1.40 and 3.42 respectively. However, the important factor is that there is a relatively minor change within the length ratio of second- and third-order streams for basin III B as compared to basins III A and III C. Hence, basin III B is likely to be underlain by rocks of greater homogeneity than in basins III A and III C.

Lengths of the streams of the same order, and especially of the first order, in different basins can be used to compare the drainage efficiency (Wisler and Brater 1959). Table 3 illustrates that in some of the second-order basins, the mean lengths of first-order streams are quite high (i.e. greater than 0.5 km; e.g. in basins 1, 8, 9, 10, 11 and 12). In these basins, the rocks

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Table 4 Drainage characteristics of second-order basins of the Kurzadi watershed—Part II

Basin	Order of basin	No. of streams N	Basin area A (km^2)	Total length of streams L (km)	Drainage density D_d=L/A (km/km^2)	Constant of channel maintenance C=1/D_d (km^2/km)	Stream frequency F=N/A (per km^2)	Length of overland flow L_g=1/2D_d (km^2/km)
1	2	5	1.63	4.50	2.76	0.36	3.07	0.18
2	2	5	0.76	2.65	3.49	0.29	6.58	0.14
3	2	3	0.42	1.25	2.98	0.34	7.14	0.17
4	2	4	0.34	1.60	4.71	0.21	11.76	0.11
5	2	3	0.33	1.10	3.33	0.30	9.09	0.15
6	2	3	0.31	1.25	4.03	0.25	9.68	0.12
7	2	3	0.41	1.25	3.05	0.33	7.32	0.16
8	2	3	0.69	1.80	2.61	0.38	4.35	0.19
9	2	3	0.67	2.75	4.10	0.24	4.48	0.12
10	2	3	1.12	2.30	2.05	0.49	2.68	0.24
11	2	3	1.05	2.40	2.29	0.44	2.86	0.22
12	2	3	1.05	3.45	3.29	0.30	2.86	0.15

over which the first-order streams are developed are more permeable compared to those of other second-order basins. Most of the first-order sub-basins are in close proximity to contacts between basalt units where permeabilities are relatively high.

Drainage Density (D_d)

The drainage density is an indicator of the linear scale of landform elements in a stream-eroded topography (Horton 1945). It is the ratio of the total stream length of all orders within a basin to the area of the basin. It is indicative of the closeness of spacing of the streams and also the texture of the drainage basin. Table 2 shows that the fourth-order Kurzadi basin has an average drainage density of 2.62 km/km^2 and is indicative of a medium-textured drainage basin. The three third-order basins of the Kurzadi watershed (III A, III B, and III C) have average drainage densities of 3.95, 2.85 and 3.22 km/km^2 respectively, which shows that the runoff is less in basin III B as compared to that in basins III A and III C. A significant correlation to this could be the higher permeability of the rocks exposed in basin III B. Table 4 gives the drainage densities calculated for the second-order basins of the Kurzadi watershed. A comparison of the drainage densities of these second-order basins shows that some of them have lower values than the average drainage density (2.62 km/km^2) calculated for the fourth-order Kurzadi basin. These second-order basins are 8, 10 and 11. The lowest value of 2.05 km/km^2 occurs in basin 10. The rock surfaces drained by these second-order basins appear to be highly permeable because they include the weathered tops of amygdaloidal basalt, which are exposed in the basin.

Constant of Channel Maintenance (1/D_d)

Schumm (1956) introduced the factor, constant of channel maintenance, as the inverse of the drainage density. It is also the area required to maintain one linear kilometre of stream channel. Generally, a higher constant of channel maintenance of a basin indicates higher permeability of the rocks of that basin, and vice versa. Table 2 shows that the fourth-order Kurzadi basin has a constant of channel maintenance of 0.38 km^2/km. This means that an area of 0.38 km^2 is required to maintain one kilometre of stream channel. The table also shows that the third-order basin III B has a higher constant of channel maintenance (0.35 km^2/km) than the third-order basin III A (0.25 km^2/km) and third-order basin III C (0.31 km^2/km). A larger area is required in basin III B to maintain one kilometre of the stream channel, indicating a relatively higher permeability of the rocks in this basin. The values of the constant of channel maintenance for the second-order basins are given in Table 4. Basins 10 and 11 show values higher than the average value for the fourth-order Kurzadi basin (0.38 km^2/km). Basin 10 shows the highest value of 0.49 km^2/km. The larger area required to maintain one kilometre of the stream in basin 10 implies the occurrence of higher permeability rocks in this basin.

Stream Frequency (F)

Horton (1932) proposed the stream frequency factor as the ratio of the total number of streams in a basin to the basin area. A higher stream frequency points to a larger surface runoff and steeper ground surfaces. The stream frequency for the fourth-order Kurzadi basin is 3.14 per km^2 (Table 2), which means that three streams are developed in an area of one square kilometre in the basin. Table 2 shows that the third-order basins of the Kurzadi watershed (III A, III B and III C) give stream frequency values of 8.64, 4.07 and 5.53 per km^2 respectively. The lower value of stream frequency for the basin III B shows that it has gentler ground slopes and more permeable rocks in relation to the basins III A and III C. The values of stream frequencies for the second-order basins, given in Table 4, show that basins 4, 5 and 6 have high values of

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stream frequency, indicating steeper slopes and lower permeability of the rocks within these basins.

Length of Overland Flow (L_g)

The length of overland flow (L_g) is the length of streamflow paths, projected to the horizontal from the point of drainage divide to a point on the adjacent stream channel. The average length of overland flow is equal to half the reciprocal of the average drainage density (1/[$2D_d$]). The length of overland flow averages the downslope flow paths, from the drainage divide to the nearest channel. The length of overland flow also points to the efficiency of the drainage in the basin. The length of overland flow for the fourth-order Kurzadi basin is 0.19 km^2/km, as given in Table 2. A larger value of length of overland flow indicates longer flow paths and thus, gentler slopes. The values of length of overland flow for the third-order basins III A, III B and III C are 0.13, 0.18 and 0.16 km^2/km respectively, pointing to gentler slopes and longer flow paths for the basin III B (Table 2). The value for length of overland flow for the second-order basins, given in Table 4, show that some of the basins have higher values than the average value for the fourth-order Kurzadi basin, i.e. basins 10 (0.24 km^2/km) and 11 (0.22 km^2/km).

Variation in Permeability of Rock Surfaces – Kurzadi Drainage Basin

The drainage or morphometric analysis provides information on the variation in the permeability of the aquifer units exposed in the Kurzadi basin. The data given in Tables 1 and 2 show that rock surfaces in the third-order basin III B are more permeable than those in third-order basins III A and III C. This is indicated by the higher values of $1/D_d$ and L_g, and lower values of D_d and F for this basin as compared to the basins III A and III C. The basalt-flow units exposed in both the third-order basins III A and III B are the same, viz. CB-2, VAB-2 and CB-3. Vesicular-amygdaloidal-basalt-flow units possess better storage and transmission capabilities than compact basalt-flow units (Kulkarni et al. 2000). The amygdaloidal-basalt-flow unit VAB-1 is the principal component of the groundwater system in all three basins. It is likely to possess higher storage and transmission characters by virtue of its pronounced degree of weathering, particularly compared to the compact basalt-flow units CB-2 and CB-3. However, the permeability of its exposed rock surface in basin III B is likely to be greater than the permeability of its surfaces rock exposed in basins III A and III C. The higher value of length ratio of fourth- to third-order streams of basin IV indicates that the surface of the amygdaloidal-basalt-flow units VAB-1, over which the fourth-order stream of basin IV flows, is more permeable, as compared to those of the third-order basins III A, III B and III C.

A comparison of the drainage parameters of the second-order basins can demarcate the probable areas of higher permeability. The streams of the second-order basins with higher length ratios, 1 (1.54), 2 (1.43) and 11 (1.09), flow over the amygdaloidal-basalt-flow unit VAB-2 and the higher length ratios for these basins point to the higher permeability of the surface of amygdaloidal-basalt-flow units VAB-2 exposed in these basins. Table 3 shows that the mean first-order stream lengths, greater than 0.5 m for the basins 1, 8, 9, 10, 11 and 12, also suggest a higher permeability of the flow units VAB-1 and VAB-2 wherever they are exposed in these basins. Similarly, Table 4 shows that some of the second-order sub-basins have low values of D_d (<3 km/km^2), high values of $1/D_d$ (>0.3 km^2/km) and high values of L_g (>0.15 km^2/km), namely sub-basins 1, 3, 8, 10 and 11. The first- and second-order streams in these basins flow over the amygdaloidal-basalt-flow units VAB-1 and VAB-2, and the drainage parameters point to a high permeability of the rock surface of these flow units wherever they are exposed in these basins, although the relative magnitude of slopes would also control the infiltration values to some extent. Broadly, sub-basins 1, 8, 10 and 11 bear strong indications of permeable rock surfaces and/or gentler slopes. These could be the better areas for rainfall infiltration and therefore could constitute favourable areas for recharge to the groundwater systems of the lower reaches of the Kurzadi basin.

Strategy for Treatment of Kurzadi Watershed

Third-order basins such as the ones in the Kurzadi basin are typical microwatersheds selected for 'treatment' under various watershed-development programmes in India. Considering the drainage characteristics derived in the present study, a strategy can be proposed in the Kurzadi sub-basins for various measures. Table 5 describes a broad strategy, including the types of measures to be undertaken in various third-order basins of the Kurzadi basin, based on the drainage indices obtained in the foregoing discussion. The second-order sub-basins 8, 10 and 11 are the most suitable for implementing recharge measures within the Kurzadi basin (order IV). Basin III B is the most suitable for recharge-related work as it has relatively gentler gradients and higher rock-surface permeability. VAB-2, exposed over large portions of this basin, is likely to serve as conductive medium for the recharged water. The second-order sub-basin 1 is the most suitable for implementing recharge measures within basin III B. On the other hand, basin III A is better suited to harvest runoff and store it on the surface, rather than to augment groundwater recharge. This is because of lower rock-surface permeability and steeper land-surface gradients, largely attributed to CB-2 and CB-3. Second-order sub-basin 6 is most suitable for surface-water augmentation within basin III A. Finally, basin III C can be used partly for recharge and partly for augmenting surface-water resources since values indicated by various drain-

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Table 5 Strategy for watershed-treatment measures based on drainage characteristics of third-order sub-basins of the Kurzadi watershed

Basin	Order of basin	No. of streams N	Basin area A (km^2)	Total length of streams L (km)	Watershed development approach-recharge/surface-water augmentation	Treatment on lower (second-order) streams (see Table 4)
IV	4	60	19.08	49.95	Groundwater-resource development	Recharge measures in 8, 10 and 11
III A	3	7	0.81	3.20	Surface-water augmentation	Surface-water augmentation in 6
III B	3	15	3.69	10.50	Groundwater-recharge measures	Recharge measures in 1
III C	3	11	1.99	6.40	Recharge and surface-water augmentation	Surface-water augmentation in 4; recharge measures in 3

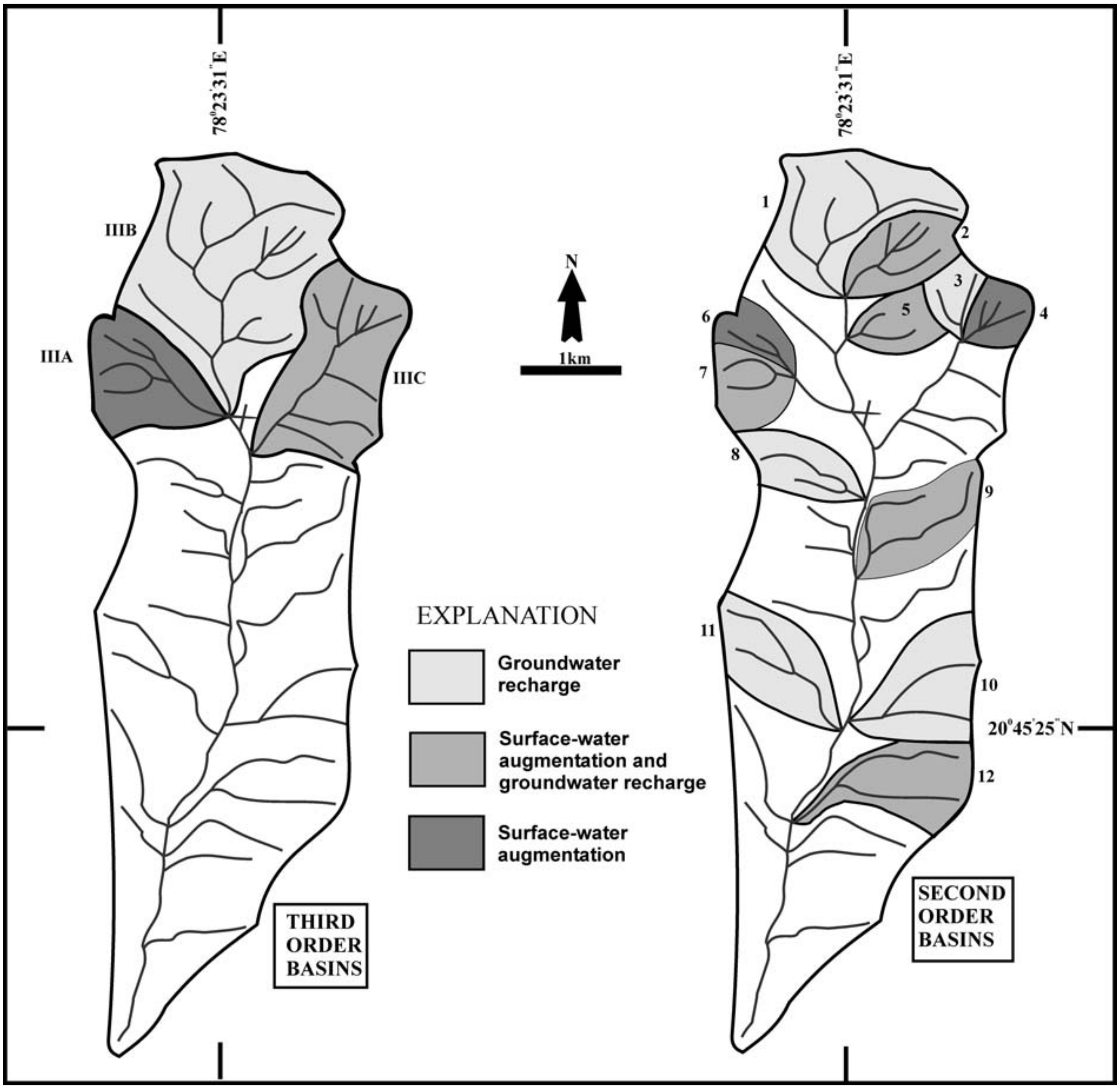

Fig. 4 Broad plan for recharge and surface-water augmentation within the Kurzadi watershed

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age indices fall between the values for basins III A and III B. Second-order sub-basin 3 is most suitable for recharge within basin III C, whereas sub-basin 4 could be used for augmenting surface-water resources.

Although the strategy suggested here is broad, it constitutes a systematic approach that provides a platform to conduct detailed surveys to select specific sites and measures. Thus, on the basis of this hydrogeological study, it is possible to demarcate suitable areas for the proper siting of recharge measures (Fig. 4) at the planning stage.

Conclusions

Sites for recharge and runoff harvesting in watershed-development programmes in India are selected either on an 'ad hoc' basis or based solely on topographic considerations. Recharge sites are particularly poorly sited either because the rock-surface permeability of the substrate is not considered or because these sites are often located in natural groundwater discharge areas. Drainage-analysis values form a useful tool in selecting such sites because they provide comparative indices of the permeability of rock surfaces in various parts of a drainage basin. If this is combined primarily with the observed hydrogeological characteristics of the drainage basin, the strategy of siting recharge and water-harvesting measures is rendered effective.

For the Kurzadi river basin, the third-order basin III B is more permeable to infiltration than the third-order basins III A and III C, as indicated by the higher values of the constant of channel maintenance ($1/D_d$) and length of overland flow (L_g), and the lower values of drainage density(D_d) and stream frequency (F). Moreover, larger areas of basin III B are likely to be permeable since length ratio (R_l) data indicate more homogeneous surfaces for basin III B as compared to surfaces in basins III A and III C where the permeable rock surfaces would be restricted only to areas through which the third-order stream flows. In the field, the permeability of such surfaces is manifested through the more pronounced weathering of the amygdaloidal-basalt-flow units which, when highly weathered, contain open and conductive fractures and joints.

The relatively permeable nature of the fourth-order basin is mainly accounted for by the basalt-flow unit VAB-1. The higher values of the length ratio of fourth- and third-order streams of basin IV indicate that the surface of the amygdaloidal-basalt-flow unit VAB-1, over which the fourth-order stream of basin IV flows, is gentler in slope and more permeable, as compared to rock surfaces of the third-order basins III A, III B and III C. VAB-1 is also typically sheet-jointed and forms the major unconfined aquifer in the Kurzadi watershed. VAB-1 forms natural-discharge zones, which contribute to the base flow as observed at many places along the stream channels.

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