The Relationship between Macro-Topography and the Groundwater Quality in the Great Fish River Basin, Eastern Cape Province

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Abstract

The Great Fish River Basin can be divided into the following geomorphologic regions which are easily recognizable: the Marginal Region, the Great Escarpment, the Headbasin and the Interior Plateau. There is also a distinct relationship between these regions and the quality of the groundwater located in them.

The main differences are observed in the concentration of Ca^{++} and HCO_3^- as opposed to the concentration of Na^+ and Cl^-. High percentages of Ca^{++} and HCO_3^- are observed in the higher lying Interior Plateau, whilst high Na^+ and Cl^- percentages are encountered in the groundwater of the Headbasin and Marginal Region. The latter two regions represent areas of low relief where groundwater movement becomes almost stagnant.

The change in groundwater quality from the Interior Plateau to the Headbasin is gradual and the quality of these waters is distinctly different from that of the Marginal Region. This difference may be attributed partly to the influence of connate marine waters from the sedimentary rocks of the Dwyka Formation and Ecca Group which are encountered in the latter region and partly to the atmospheric fall-out of salts. Extremely high Cl^- and Na^+ concentrations are encountered here.

Introduction

The area in review comprises a map-area of about 25 000 km^2 and is located between longitudes 25° E to 27° E and latitudes 31°15'S to 33°15'S (Figs. 1 and 2).

In the area most of the annual precipitation (350—450 mm) occurs between February and March when evapotranspiration is at its highest. The runoff from the basin amounts to only 3 per cent of the above precipitation (Tordiffe, 1978) whilst the rest of the water either evaporates immediately or is temporarily stored in the soil before being lost to the atmosphere by means of evapotranspiration.

As a result of the semi-arid climate of the area, the annual evapotranspiration exceeds the annual precipitation, the result being that very little of the meteoric water reaches the groundwater table. Infiltration of the meteoric water is further retarded by the presence of clay-rich (montmorillonite and other swelling clays) soils through which it is to penetrate on its way down to the groundwater table. Further proof of the high evapotranspiration rate, is the presence of a calcrete layer in the soils throughout the area. Tordiffe (1978) points out that it is only under exceptional conditions such as those which prevailed during 1974, when the precipitation exceeded even the free

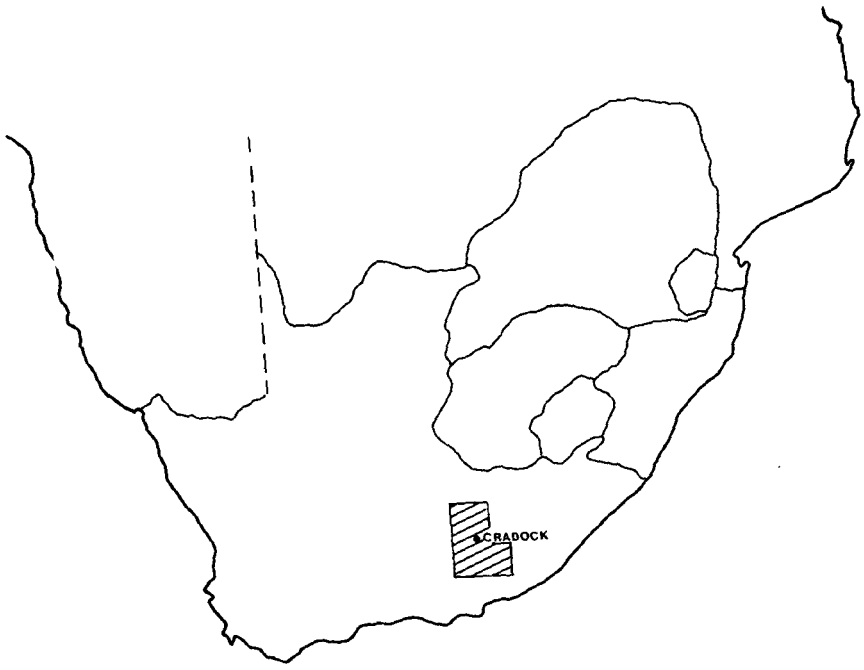

Figure 1
Locality map of the Great Fish River Basin.

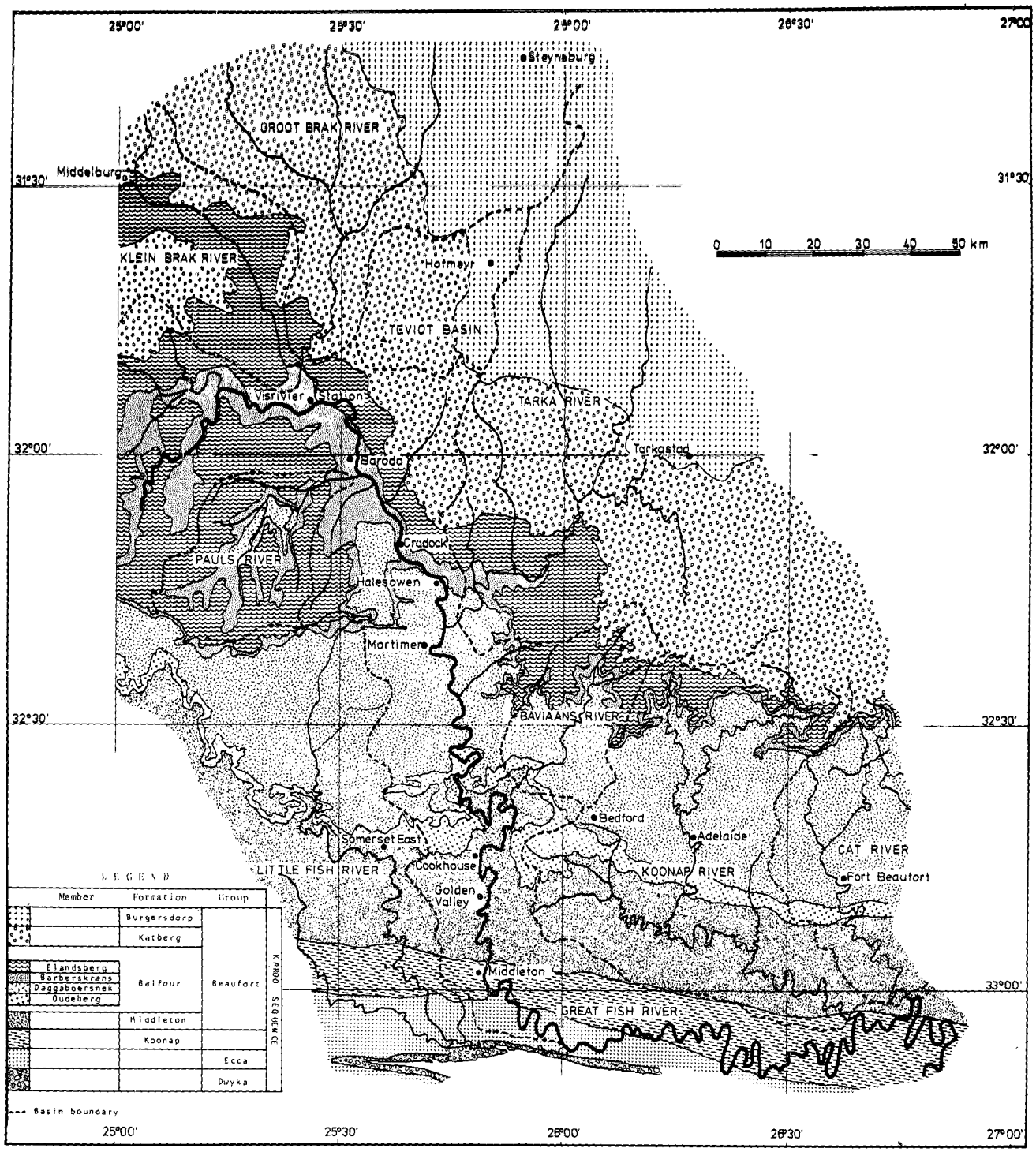

Figure 2
Simplified geological map of the Great Fish River Basin.

water evaporation, that a notable infiltration takes place.

Geologically the area is underlain by a 8 540 m sedimentary succession of the Karoo Sequence (Fig. 2). The sedimentary rocks represented here are the tillite of the Dwyka Group (680 m), alternating cycles of marine shale and sandstone of the Ecca Group (2 340 m), alternating cycles of deltaic mudstone and sandstone of the Koonap Formation (980 m) and alternating cycles of fluvial mudstone and sandstone of the Beaufort Group (4 540 m). A complex network of dolerite dykes and sills has intruded into the above sedimentary strata.

As a result of compaction, the porosity and permeability of the sedimentary rocks in the Karoo Basin are reduced to extremely low values. The groundwater in the rocks is therefore restricted mainly to joints and to fracture zones caused by the intrusion of dolerite. The water levels in most of the bore-holes therefore represent a pressure or piezometric surface rather than

an actual water table. Such levels, however, regionally represent a surface which closely resembles the surface topography, whilst the flow of groundwater is down the regional slope, the rivers acting as effluent drainage canals for the groundwater (Tordiffe, 1978).

Chebotarev (1955b) discusses the metamorphic cycle of natural waters and concludes that chloride brines, which are formed even in "fresh-water" sediments, can be attributed to the "metamorphism" of meteoric water. He also states that the salinity distribution of subterranean waters obeys a definite hydrological and geochemical law which can be formulated as the cycle of metamorphism of natural waters in the crust of weathering.

The hydrochemistry of the main environments in which the chemical quality of the groundwater in the Great Fish River Basin is affected, is discussed by Tordiffe (1978). These are the environments of condensation, precipitation, evaporation and infiltration of meteoric waters as well as the saturated zone below the groundwater level and the points of groundwater discharge. Factors such as the chemistry of water recharging the groundwater (cyclic salts present in rainfall), dissolution of minerals, the chemistry and degree of replacement of connate waters present in the sedimentary rocks, ion exchange between the water and clay minerals in the soils and sedimentary rocks, reduction of sulphate in solution by biological agents and the concentration of dissolved solids either by evaporation or by natural filtration through the sediments are discussed by Tordiffe (1978).

The degree to which chemical equilibrium is reached between the groundwater and the particular environment in which it occurs, depends largely on the length of time that the water resides in such an environment. Such a residence time is dependent on the rate of groundwater flow which in turn is dependent on the permeability of the geological strata through which it flows and on the hydraulic head which is developed. Should the permeability of the geological strata remain relatively constant throughout the area one could then assume that variations in the hydraulic head of the groundwater system are the main causes of differences in the flow rate. According to Levinson (1979) topography controls (a) the rate and amount of surface runoff and therefore the amount of moisture available for chemical reaction and (b) the rate of groundwater movement which consequently controls the rate of removal of soluble products.

The macro-topography of the Great Fish River Basin appears to exercise some influence on the rate of groundwater movement and can clearly be observed in the regional distribution of dissolved salts. Groundwater percolation is relatively good in the higher lying areas (exhibiting a high relief) as opposed to relatively stagnant conditions which prevail in the lower lying areas (exhibiting low relief). The residence time of the groundwater in the geological strata of the lower lying area is therefore much greater than in the higher lying areas, thus causing more time for chemical reactions to reach equilibrium.

Topography

The topography of the Great Fish River Basin is displayed in Fig. 3.

An outstanding feature of the South African physiography is the Great Escarpment which resulted from the African Cycle of erosion of the Post-Gondwana landscape (King, 1963).

The Post-Gondwana landscape started developing from the Middle Jurassic to Early Cretaceous Era when Gondwanaland drifted apart (King, 1963). During this era the Great Fish River must have started its development, and has ever since played an important role in the geomorphological evolution of the Eastern Cape Province.

The Great Fish River Basin may be sub-divided into the following main geomorphologic provinces: The low-lying Marginal Region (below 760 m), the Great Escarpment (760 – 1 070 m), the Headbasin (1 070 – 1 370 m) and the Interior Plateau (above 1 370 m) (Fig. 3).

The Marginal Region

Extending northwards from the Cape Fold Belt to the foot of the Great Escarpment, lies a rather undulating landscape of medium to low relief which is approximately 50 km wide in this area. The foot of the escarpment is taken as the 760 m topographic contour and is defined approximately from west to east by the towns Somerset East, Cookhouse, Bedford, Adelaide and Fort Beaufort (Fig. 3).

The tops of the undulating hills in the Marginal Region represent the older African and post-African surfaces, which have been dissected by younger erosion cycles.

An interesting feature of this region is the meandering nature of the rivers, e.g. the Great Fish, Little Fish, Koonap and Cat Rivers.

According to King (1963) this area belongs to the Karoo province of the Marginal Region. A southerly extension of the Bruintjieshoogte range, however, clearly separates this region from the typical Karoo landscape to the west.

The Great Escarpment

The Great Escarpment is an area of high relief lying between the 760 m and 1 370 m topographic contours (Fig. 3).

King (1963) states that although this feature is not an escarpment in the strict sense of the term, it, however, always constitutes a relatively sharp rise from the Marginal Region to the high Interior Plateau. This description is also applicable to the present area. Here the Great Fish River has gnawed into the Great Escarpment at a far greater pace than its own tributaries (Little Fish, Koonap and Cat Rivers) and some of the smaller neighbouring rivers. The result of this being the capture of a large part of the Interior Plateau in the form of a headbasin behind the escarpment.

For the purpose of this study, the Great Escarpment is regarded as passing through the Tandjiesberge, Coetzeesberge, Grootbruintjieshoogte, Bosberg, Baviaansrivierberge and Wintersberge (Fig. 3). King (1963), however, regards the above mountain ranges as the former position of the escarpment and that it now passes through Tembuland (Northern part of the Republic of Transkei) and the Suurberg, which forms the water divide between the Orange River and the Great Fish River Basin.

The Headbasin

The Great Fish River as previously mentioned has eroded part of the Interior Plateau behind the Great Escarpment. As a result an almost circular headbasin of about 100 km in diameter has developed.

Mountains such as Lootsberg, Wapadsberg, Kommetjiesberg, Graatjiesberg, Tandjiesberg, Bankberg, Gannahoekberg, Winterberg, Toorberg, Bamboesberg, Suurberg, Kikvorsberg,

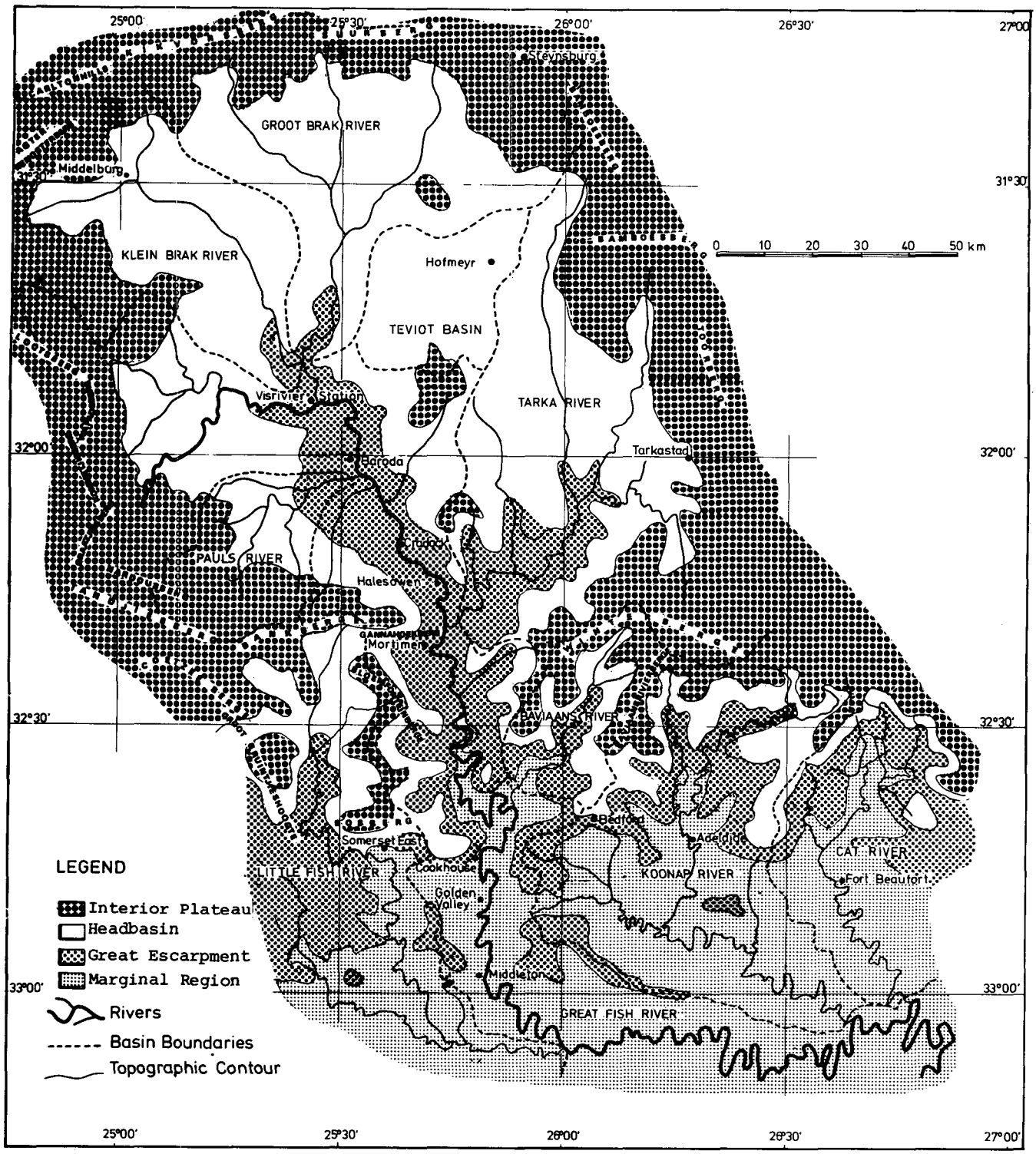

Figure 3
Topographic map of the Great Fish River Basin.

Carltonhills and Agter-Renosterberg surround the basin in an anticlockwise direction from the west (Fig. 3). A small escarpment toward the basin margin is defined by these mountain ranges. When crossing over the watershed between the Orange and the Great Fish River at the Carltonhills one can clearly see this escarpment.

At the base of the above escarpment lies a vast expanse of colluvium-covered plains which present an area of relatively low relief. On these plains bahadas have developed between scattered inselberge, mesas and buttes, which are the remains of the Interior Plateau. Tafelberg near Middelburg and Koffiebus and Teebus, near Steynsburg, are the better known of these features.

Resistant dykes of dolerite stand out as prominent elongated ridges throughout the area. One such dyke runs in a north-south direction from Middelburg, past Cradock and can

clearly be seen from Witkransnek on the main road between the two towns.

King (1963) regards this basin as part of the Eastern Uplands which belong to the Marginal Region.

The largest part of this headbasin lies between the 1 060 m and 1 370 m topographic contours.

The Interior Plateau

This geomorphologic province constitutes the water divide between the Great Fish River Basin and the Orange, Kei and Sundays Rivers.

Bevelling by the Africa Cycle of erosion has resulted in scattered mountain ranges of which the dolerite-capped tops represent remnants of the Post-Gondwana Plateau. The only part of the area which can still clearly be recognised as a plateau, is that to the north of Steynsburg, represented by the Suurberg and Kikvorsberg.

Groundwater Quality and the Topography

Sampling Procedure and Chemical Analysis

The chemical analyses of the groundwater samples collected lin the area are presented in Tables 1 to 4. These samples were collected within a period of two weeks in order to reduce the possibility of changes in the groundwater quality with time. Samples were collected from existing boreholes nearest to a grid of approximately 12 km x 12 km, as the sampling of all existing boreholes in the area would have been a near impossible task. Hem (1970) is of the opinion that although it is doubtful whether a single water sample from a borehole represents the chemical composition of all the groundwater in the vertical section at that point; it is, however, a useful indication of the average composition.

The types of soluble salts which are contained in natural waters, according to Cheboratev (1955a), remain largely unchangeable, and therefore, he uses only the ions Na^+, K^+, Ca^{++}, Mg^{++}, Cl^-, HCO_3^-, $CO_3^=$ and $SO_4^=$ to determine and express the possible chemical reactions and properties of water.

Chebotarev (1955a) recognises the following three major categories of natural waters which practically cover all the variety of the chemical compositions of subterranean waters: (a) bicarbonate waters, (b) sulphate waters and (c) chloride waters. Because of the regional scale on which this investigation was conducted, it was decided to analyse only for the ions mentioned above.

Two 500 ml polythene containers were filled with water from each particular sampling point. A few drops of dilute HCl were then added to one sample in order to prevent any $CaCO_3$ precipitation, whilst the other sample was used for determining the concentrations of the rest of the ions present. All samples were collected from boreholes on which windmills are erected and care was taken to ensure that the mill had been pumping water for at least 15 min before collecting the sample. The pH of the water was determined on the sampling site.

The cations were determined by means of atomic-absorption spectrophotometry and flame emission spectrography, whilst the anions were determined by titration-methods. Analy-

TABLE 1
INORGANIC QUALITY OF GROUNDWATER SAMPLES FROM THE INTERIOR PLATEAU

SAMPLE No	CO-ORDINATES Lat. S	Long. E	CATIONS Na^+ mg/ℓ	K^+ mg/ℓ	Mg^{++} mg/ℓ	Ca^{++} mg/ℓ	ANIONS Cl^- mg/ℓ	(HCO_3^-) mg/ℓ	$SO_4^=$ mg/ℓ	TDS mg/ℓ	pH
1 – 1	31°15′	25°00′	29,2	0,4	18,2	56,1	27	262	28	421	7,7
1 – 2	31°15′	25°07½′	26	0,7	15,5	26,1	18	171	23	280	8,0
1 – 3	31°15′	25°15′	20,6	1	19,2	44,1	20	226	19	350	7,7
1 – 6	31°15′	25°37½′	25	0,3	29,6	46,1	18	311	9	439	8,0
1 – 9	31°15′	26°00′	24	0,6	25,6	80,2	22	296	31	479	7,6
2 – 1	31°22½′	24°52½′	20,3	0,5	38,8	19,1	28	232	19	358	7,8
2 – 2	31°22½′	25°00′	32,1	0,7	22	46,1	20	281	15	417	7,5
2 – 3	31°22½′	25°07½′	63,6	0,8	31,6	24,6	64	262	28	475	7,8
2 – 9	31°22½′	25°52½′	29,3	2,5	31,4	38,1	24	305	4	434	8,0
2 – 10	31°22½′	26°00′	67	1,7	30,8	48,1	38	378	28	591	7,6
3 – 1	31°30′	24°45′	26,8	1	35,4	8,7	57	153	14	296	7,7
4 – 1	31°37½′	24°45′	22,9	0,8	41,6	26,1	17	287	28	423	7,8
5 – 2	31°45′	25°00′	27	1,2	39,2	7,5	35	226	5	341	7,8
5 – 12	31°45′	26°15′	79,5	1,4	35	46	76	323	61,8	623	7,8
6 – 11	31°52½′	26°15′	32,5	0,5	10	28	26	171	1,04	269	7,8
7 – 1	32°00′	25°00′	69	0,7	18	17	58	189	30,9	383	7,9
8 1	32°07½′	25°00′	29,5	0,7	26	42	25	293	1,3	417	8,0
8 – 2	32°07½′	25°07½′	36	2	18	16	27	189	1,6	289	7,8
8 – 11	32°07½′	26°15′	48,2	1,4	21	64	42	323	23	522	7,8
8 – 12	32°07½′	26°22½′	57,5	1	33	42	61	299	37	531	8,0
9 2	32°15′	25°07½′	14,1	0,6	9	16	20	98	1,9	160	8,0
9 – 11	32°15′	26°15′	17,8	1	10	18	21	122	1	191	7,7
9 12	32°15′	26°22½′	45,5	2,6	30	66	57	329	36	567	7,5
10 2	32°22½′	25°22½′	31,4	1	24	42	38	201	54	391	7,8
10 – 7	32°22½′	26°00′	50,5	1	34	34	40	317	17	494	7,9

TABLE 2
INORGANIC QUALITY OF GROUNDWATER SAMPLES FROM THE HEADBASIN

SAMPLE No	CO-ORDINATES Lat. S	Long. E	CATIONS Na^+ mg/ℓ	K^+ mg/ℓ	Mg^{++} mg/ℓ	Ca^{++} mg/ℓ	ANIONS Cl^- mg/ℓ	(HCO_3^-) mg/ℓ	$SO_4^=$ mg/ℓ	TDS mg/ℓ	pH
2 — 4	31°22½′	25°15′	57,5	1	44	16,4	50	293	36	498	7,9
2 — 5	31°22½′	25°22½′	18,9	2	39,2	28,1	21	277	7	393	7,6
2 — 6	31°22½′	25°30′	61,5	4,2	35,2	40,1	44	318	59	562	7,8
2 — 8	31°22½′	25°45′	29,4	1,5	38,4	24	12	323	5	433	7,6
3 — 3	31°30′	25°00′	129	2,4	16,4	54,1	111	281	95	689	7,8
3 — 6	31°30′	25°22½′	40,4	2,9	40,6	27,1	92	210	22	435	7,6
3 — 7	31°30′	25°30′	65,5	0,2	28,6	16,8	67	159	67	404	7,9
3 — 8	31°30′	25°37½′	300	17	14,8	126,3	431	311	180	1380	7,8
3 — 9	31°30′	25°45′	100	0,1	45,4	4,2	43	397	28	618	8,2
3 — 10	31°30′	25°52½′	36,4	6	43,2	18	34	279	32	449	8,3
3 — 11	31°30′	26°00′	70	6	34,4	38,1	44	264	114	569	8
4 — 3	31°37½′	25°00′	61,5	1,6	25,3	86,2	39	435	41	690	7,7
4 — 4	31°37½′	25°07½′	42,6	1,4	37,4	28,1	53	251	39	453	8,2
4 — 5	31°37½′	25°15′	125	1,4	38,9	22,9	100	342	66	696	7,7
4 — 6	31°37½′	25°22½′	40,4	2,9	40,6	27,1	92	210	22	435	7,6
4 — 7	31°37½′	25°30′	94,3	5	20,6	37,2	106	234	48	545	7,6
4 — 10	31°37½′	25°52½′	200	2	36,8	6,3	206	372	7	830	7,8
5 — 3	31°45′	25°07½′	21	1,1	24	36	18	256	3	359	7,5
5 — 4	31°45′	25°15′	11,5	1,1	25	12	9	177	1,2	237	7,6
5 — 5	31°45′	25°22½′	117,2	2	15	43	108	293	33,4	611	7,6
5 — 6	31°45′	25°30′	232	4,7	45	43	220	397	154	1095	7,8
5 — 7	31°45′	25°37½′	124	4,5	76	28	160	393	98	882	7,5
5 — 8	31°45′	25°45′	35,4	2,3	62	5	82	214	55,3	456	7,8
5 — 9	31°45′	25°52½′	270	4,8	45	20	206	525	101,6	1173	7,7
5 — 10	31°45′	26°00′	150	8,3	41	17	106	403	72	797	7,9
5 — 11	31°45′	26°07½′	49,5	1,6	36	38	26	366	18	535	7,7
6 — 1	31°52½′	25°00′	31	0,7	42	6	35	220	25,7	361	7,9
6 — 2	31°52½′	25°07½′	154	3,1	27	44	123	342	100,4	769	7,7
6 — 3	31°52½′	25°15′	45,6	2,8	83	22	163	311	12,9	640	7,5
6 — 4	31°52½′	25°22½′	58	5	22	56	68	262	52,8	523	7,8
6 — 7	31°52½′	25°45′	36	1,8	73	14	60	378	18	581	7,9
6 — 10	31°52½′	26°07½′	40,5	1,6	33	16	45	220	21,9	378	8,1
7 — 7	32°00′	25°45′	103,5	3	52	30	125	305	88	707	7,6
7 — 8	32°00′	25°52½′	87	5,7	48	54	103	360	80	738	7,7
7 — 10	32°00′	26°07½′	31,4	1,6	47	22	22	348	4	476	7,9
7 — 11	32°00′	26°15′	108	14	60	65	210	348	74,6	879	7,6
8 — 3	32°07½′	25°15′	55	1,6	38	38	49	311	47,6	540	7,9
8 — 8	32°07½′	25°52½′	92	3,3	42	8	100	232	68	545	8,0
8 — 10	32°07½′	26°07½′	80	0,3	30	38	75	317	30	569	8,2
9 — 6	32°15′	25°37½′	1694	9	314	1112	4875	61	869	8934	7,6
9 — 7	32°15′	25°45′	853	3,9	94	265	1638	153	447	3454	6,9
10—4	32°22½′	25°37½′	110	1	14	14	41	288	40	508	7,8
10 — 6	32°22½′	25°52½′	73	0,8	27	22	44	288	26	481	7,8

TABLE 3
INORGANIC QUALITY OF GROUNDWATER SAMPLES FROM THE GREAT ESCARPMENT

SAMPLE No	CO-ORDINATES Lat. S	Long. E	CATIONS Na^+ mg/ℓ	K^+ mg/ℓ	Mg^{++} mg/ℓ	Ca^{++} mg/ℓ	ANIONS Cl^- mg/ℓ	(HCO_3^-) mg/ℓ	$SO_4^=$ mg/ℓ	TDS mg/ℓ	pH
10 — 8	32°22½′	26°07½′	50,5	1	34	34	42	320	16	498	7,9
11 — 3	32°30′	25°37½′	134	1,2	50	28	120	470	19	822	7,8
11 — 4	32°30′	25°45′	1035	4	4	215	1960	0	44	3262	5,1
11 — 7	32°30′	26°07½′	88,5	1,2	37	7,5	55	336	9	534	8,1
11 — 8	32°30′	26°15′	49	1,6	23	26	47	250	1	398	7,8
12 — 5	32°37½′	25°52½′	400	3,9	110,6	34,1	677	287	201,7	1715	8,0
13 — 2	32°45′	25°30′	254	12	51	21	387	249	75	1049	7,8
13 — 4	32°45′	25°45′	680	9	117	58	1029	544	209	2646	7,6

TABLE 4
INORGANIC QUALITY OF GROUNDWATER SAMPLES FROM THE MARGINAL REGION

SAMPLE No	CO-ORDINATES Lat. S	Long. E	CATIONS Na^+ mg/ℓ	K^+ mg/ℓ	Mg^{++} mg/ℓ	Ca^{++} mg/ℓ	ANIONS Cl^- mg/ℓ	(HCO_3^-) mg/ℓ	$SO_4^=$ mg/ℓ	TDS mg/ℓ	pH
13 – 5	32°45′	25°52½′	1505	6	171	49	2581	414	121	4847	7,8
13 – 8	32°45′	26°15′	238	3	47	36	376	313	23	1036	7,8
13 – 10	32°45′	26°30′	692	3,4	123	42	1090	438	216	2604	7,5
14 – 6	32°52½′	26°00′	386	17	50	46	575	354	82	1510	7,6
14 – 7	32°52½′	26°07½′	460	11,5	73	24	675	368	118	1730	7,8
14 – 8	32 – 52½′	26°15′	235	12	58	64	334	476	112	1291	7,6
14 – 10	32°52½′	26°30′	434	10	56	12	548	451	69	1580	7,9
14 – 11	32°52½′	26°37½′	485	7,4	71	32	720	384	99	1798	7,8
15 – 1	33°00′	25°30′	324	10	63	62	475	476	66	1476	7,7
15 – 4	33°00′	25°52½′	152	16	33	36	210	293	42	782	7,7
16 – 4	33°07½′	26°00′	515	5,8	79	74	770	464	163	2071	7,7
16 – 6	33°07½	26°15′	411	12	85	96	635	537	154	1930	7,7
16 – 8	33°07½′	26°30′	581,6	23	147	78	1250	106	280	2466	7,6
16 – 9	33°07½′	26°37½′	4660	60	380	29	7742	683	2123	16127	8,3

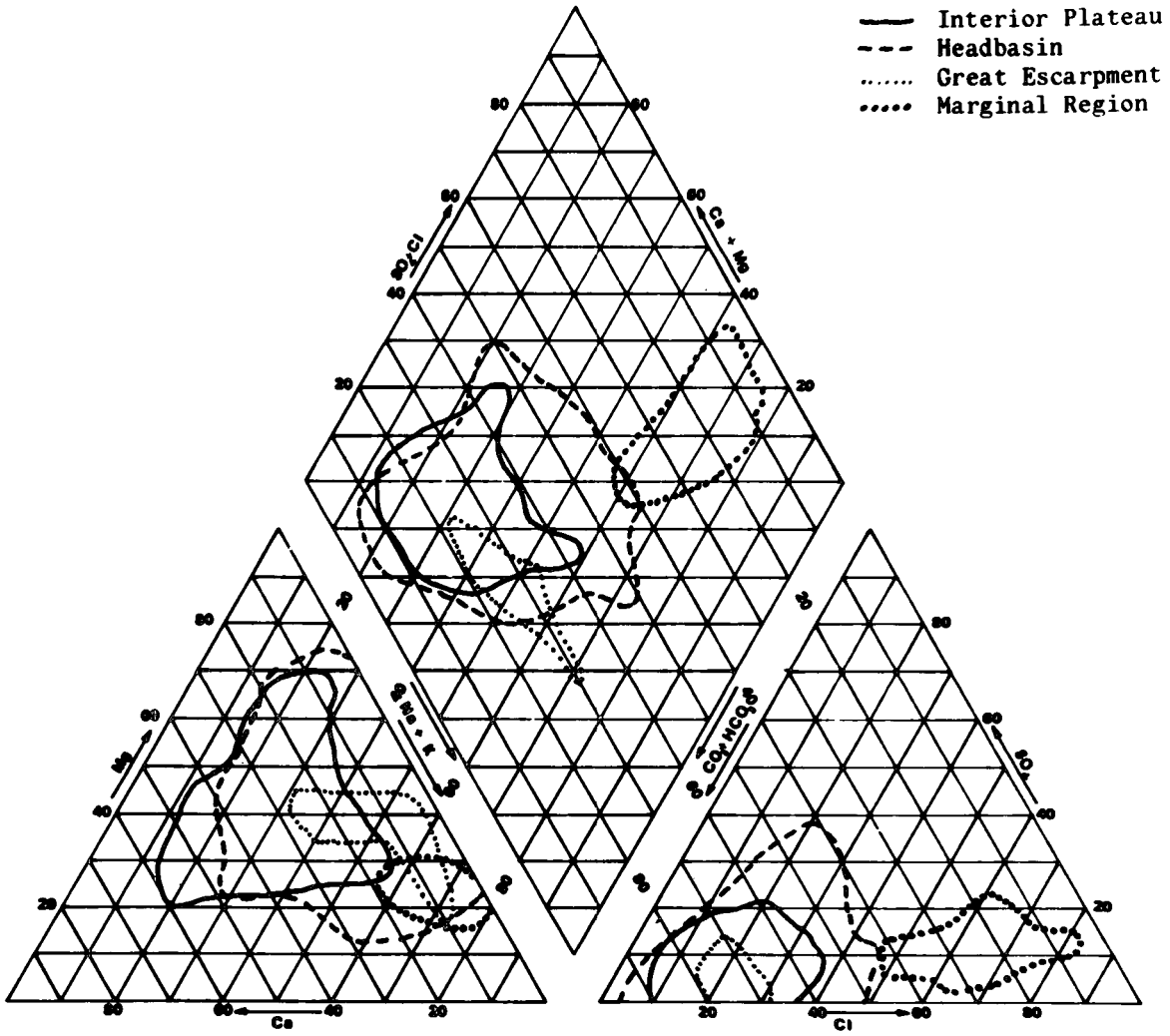

Figure 4
Trilenear presentation of the cation and anion percentge in the groundwater from the various geomorphologic regions in the Great Fish River Basin.

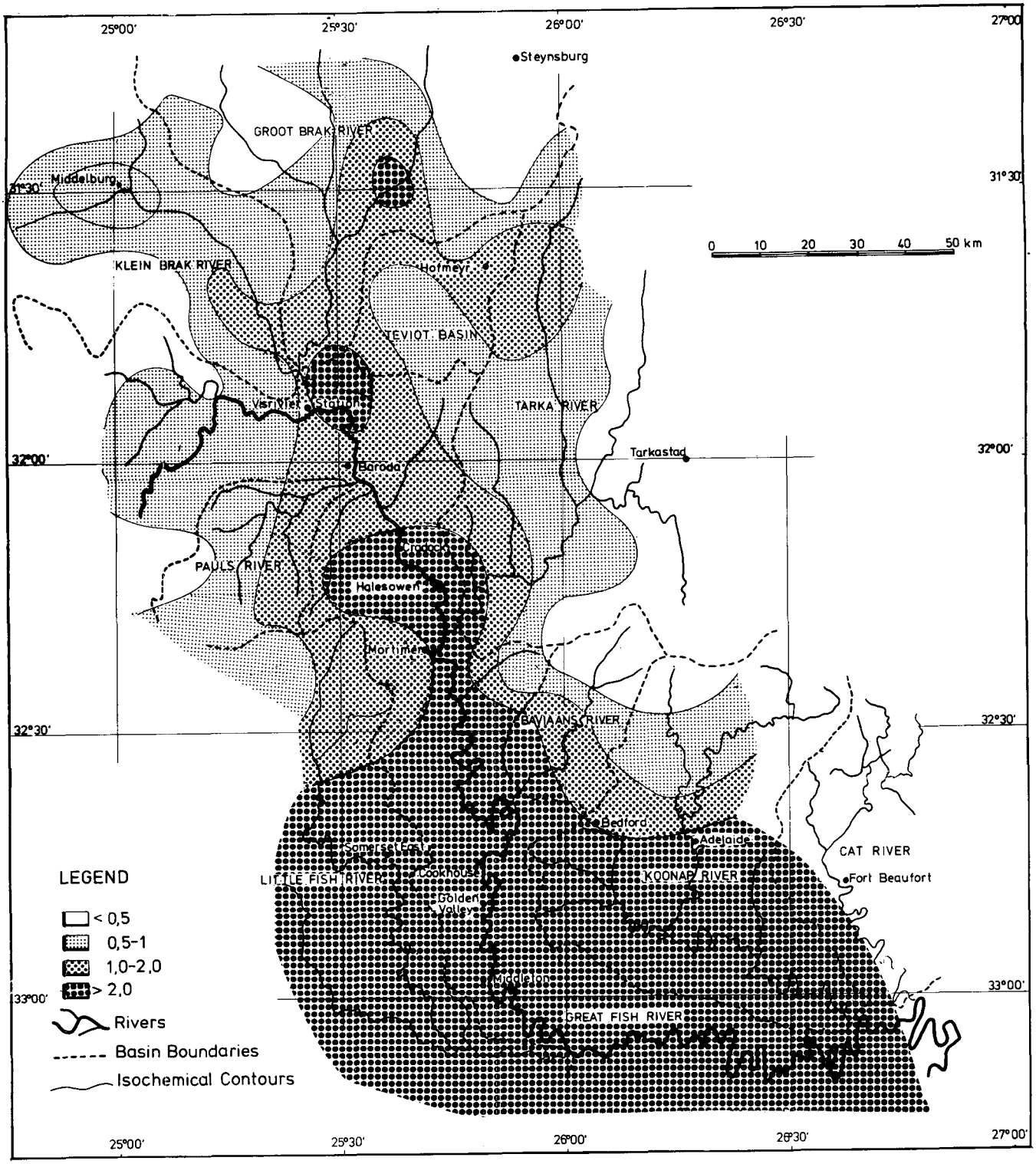

Figure 5

Isochemical contours of the $\frac{Na^+ + Cl^- + SO_4^=}{Ca^{++} + Mg^{++} + HCO_3^-}$ *ratio in the groundwater of the Great Fish River basin.*

ses of $CO_3^=$ in all the samples were so low, that the results were incorporated into the HCO_3^- concentration and expressed as total alkalinity.

Contour maps compiled from the chemical data are presented in Figs. 5 to 21. The relationship between the groundwater chemistry and the topography of the study area is illustrated by comparing the above figures with Fig. 3.

Trends in the Groundwater Quality

The general trend of the groundwater quality in the area is summarised in Fig. 4 which is a trilinear presentation of the cation and anion percentages of the above waters which are encountered in the various geomorphologic regions.

According to Fig. 4 a fair amount of overlap occurs in

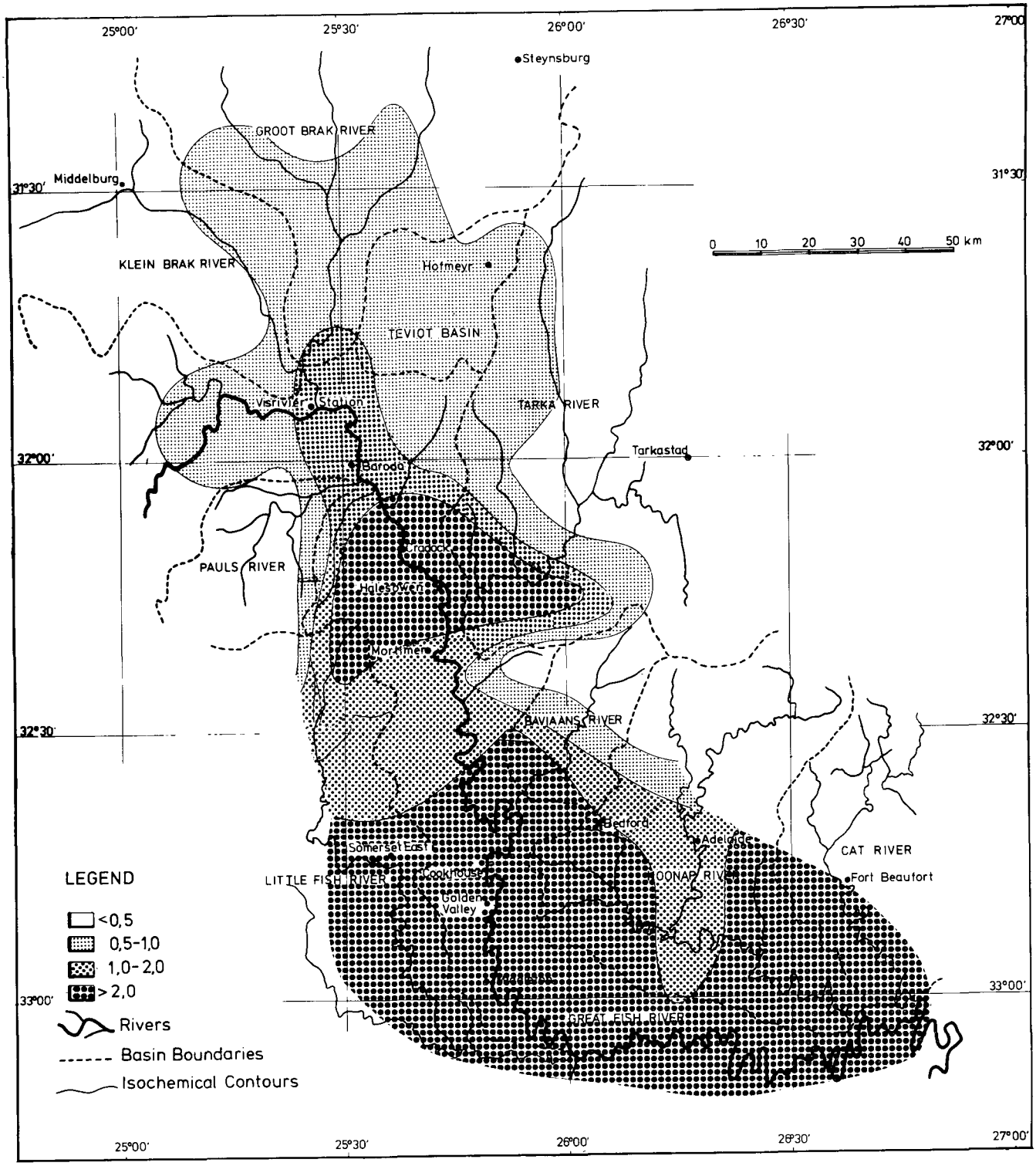

Figure 6
Isochemical contours of the chloride/bicarbonate ratio in the groundwater of the Great Fish River Basin.

both the cation and anion percentages of the groundwater from the Headbasin, Interior Plateau and Great Escarpment. In spite of this fact distinct characteristics can, however, still be observed.

As far as the cation percentages are concerned, the Interior Plateau appears to have groundwater with a predominance of Mg^{++} and Ca^{++} whilst only one sample contained Na^{+} in excess of 50% of the total cations. The groundwater from the Headbasin, however, appears to have a slightly lower percentage of Ca^{++} and a higher percentage of Na^{+}. The Great Escarpment, which in turn lies at a topographic elevation between the Interior Plateau and the Headbasin, contains groundwater which is characteristic of either of the latter regions.

In regard to the anion percentages, there appears to be a

change from HCO_3^--rich groundwater in the Interior Plateau to groundwater with slightly higher Cl^- percentages in the Headbasin. The Great Escarpment, however, contains groundwater with HCO_3^- as the predominant anion.

The groundwater from the Marginal Region, in turn, has a chemical composition which is completely different from that discussed above (Fig. 4). Groundwater samples from this area are enriched in Na^+ and Cl^-, showing almost no overlap with the groundwater quality of the other geomorphologic regions. This characteristic is especially noticeable in the anion percentages, and although the cation percentages do overlap with those from the other regions, they still tend to be concentrated in the sodium corner of the diagram.

The trends mentioned above are illustrated more directly in Figs. 5 and 6 which respectively represent the ratios $Na + Cl + SO_4/Ca + Mg + HCO_3$ and Cl/HCO_3 in the groundwater of the area. From these figures one can clearly observe the slightly higher ratios of the above ions in the groundwater of the Headbasin compared to that in the groundwater of the Interior Plateau, whilst extremely high ratios (>2) are encountered in the groundwater of the Marginal Region.

Total Dissolved Solids

Groundwater with relatively low TDS (<400 mg/ℓ) is encountered only on the Interior Plateau, as well as in the mountainous regions within the Headbasin (Fig. 7). From the plateau to the outer perimeter of the Headbasin, groundwater with a moderate concentration of TDS (400 – 600 mg/ℓ) is encountered.

The poorly-drained central parts of the Headbasin contain groundwater with a relatively high salinity (600 – 1000 mg/ℓ). It will also be noted that the Teviot Basin, in which several salt pans occur, is located within this zone.

Along the Great Escarpment the groundwater appears to contain a surprisingly high salinity (600 – 1000 mg/ℓ). This may be due to the fact that the argillaceous Daggaboersnek Member of the Beaufort Group occurs mainly in this area. Johnson (1976) points out that this sedimentary unit was probably deposited in a brackish lake environment. The saline groundwater in the Great Escarpment appears therefore to be the result of geological processes rather than the result of topographic control.

Groundwater with extremely high salinity (>1000 mg/ℓ) is located in the Marginal Region below the Great Escarpment (Fig. 7). The source of this high salinity may be attributed partly to the gradual build-up of dissolved substances as the groundwater progresses along its course down the basin and also to the presence of saline connate water from the marine deposits of the Dwyka Formation and the Ecca Group.

Apart from a few local environments where the groundwater quality is affected by factors other than topography, the general trend in the Great Fish River Basin is for the groundwater to become more saline as it moves from the higher lying areas, to the lower lying areas where more stagnant conditions are encountered.

According to Lukashev (1970) the salinity of groundwater increases with the intensity of evaporation and therefore a high salinity is associated with shallow groundwater levels.

In the Marginal region of the Basin the median depth to the groundwater level was determined as 10 m whilst a median depth of 15 m was determined for the higher lying Great Escarpment. The concentration of salts in groundwater of the former region may therefore be partly attributed to evapotranspiration.

The pH

The pH of the groundwater appears to decrease only slightly from the higher lying areas of recharge to the lower lying parts of the Headbasin and the Marginal Region (Fig. 8). This phenomenon is attributed to the hydrolysis reactions which occur during the solution of $CaCO_3$ by the newly recharged water.

The low pH of the initial meteoric water, which is caused by the solution of atmospheric and biogenic CO_2, is hereby increased as the water percolates through the soils and rock strata.

Figures 12 and 19 reveal that in the Interior Plateau, Ca^{++} and HCO_3^- respectively constitute the major proportions of the dissolved cations and anions in the groundwater.

The lower pH values which occur in the central part of the Headbasin and in the Marginal Region are apparently associated with relatively stagnant groundwater conditions.

Sodium

It is reported by Hem (1970) that once sodium is brought into solution, it tends to remain there because of the fact that there are no significant precipitation reactions which can maintain low sodium concentrations in natural waters. The only way sodium may be retained in the solid phase is by adsorption on clay minerals in the soil or in sedimentary rocks. Because of the preferential adsorption of Ca^{++} above Na^+, only small amounts of sodium are, however, retained this way in the study area (Tordiffe, 1978).

As the groundwater progresses into the basin, the Ca^{++}, which was initially dissolved, is either precipitated as $CaCO_3$ or is adsorbed in exchange for Na^+. The sodium concentration of the groundwater increases along the regional flow direction. This trend is clearly observed in Figs. 9 and 10 where low Na^+-values are encountered in the groundwater of the Interior Plateau, whilst its concentration increases toward the centre of the Headbasin.

The high concentration of sodium in the Marginal Region may, however, be partly due to the presence of Na^+-rich connate water from the Dwyka Formation and from the Ecca Group (Tordiffe, 1978).

As the Marginal Region lies closest to the sea, it is quite possible that it may be a greater recipient of atmospheric salts carried in from the ocean than any of the other geomorphologic regions. No investigations of this nature have, however, been conducted in the area to prove or disprove this possibility.

Another striking fact concerning the increase in sodium in the groundwater of the area, is its direct relationship to the increase in salinity of the water (Figs. 7 and 9).

Calcium

Equilibria involving carbonates are according to Hem (1970) the major factor limiting the solubility of calcium in most natural water. Ca^{++}, because of its position in the so-called lyotropic series (Golubev and Garibyants, 1971) is easily adsorbed, especially by clay minerals and therefore has a limited mobility in relation to Na^+. This fact leads to the inverse relationship between Ca^{++} and Na^+ in groundwater and is also observed in the study area (Figs. 10 and 12).

Calcium is furthermore removed from the solution as the groundwater penetrates environments which are suitable for $CaCO_3$ precipitation.

The percentage Ca^{++} of the total cations in solution, however, reveals clearly a general pattern of limited mobility for

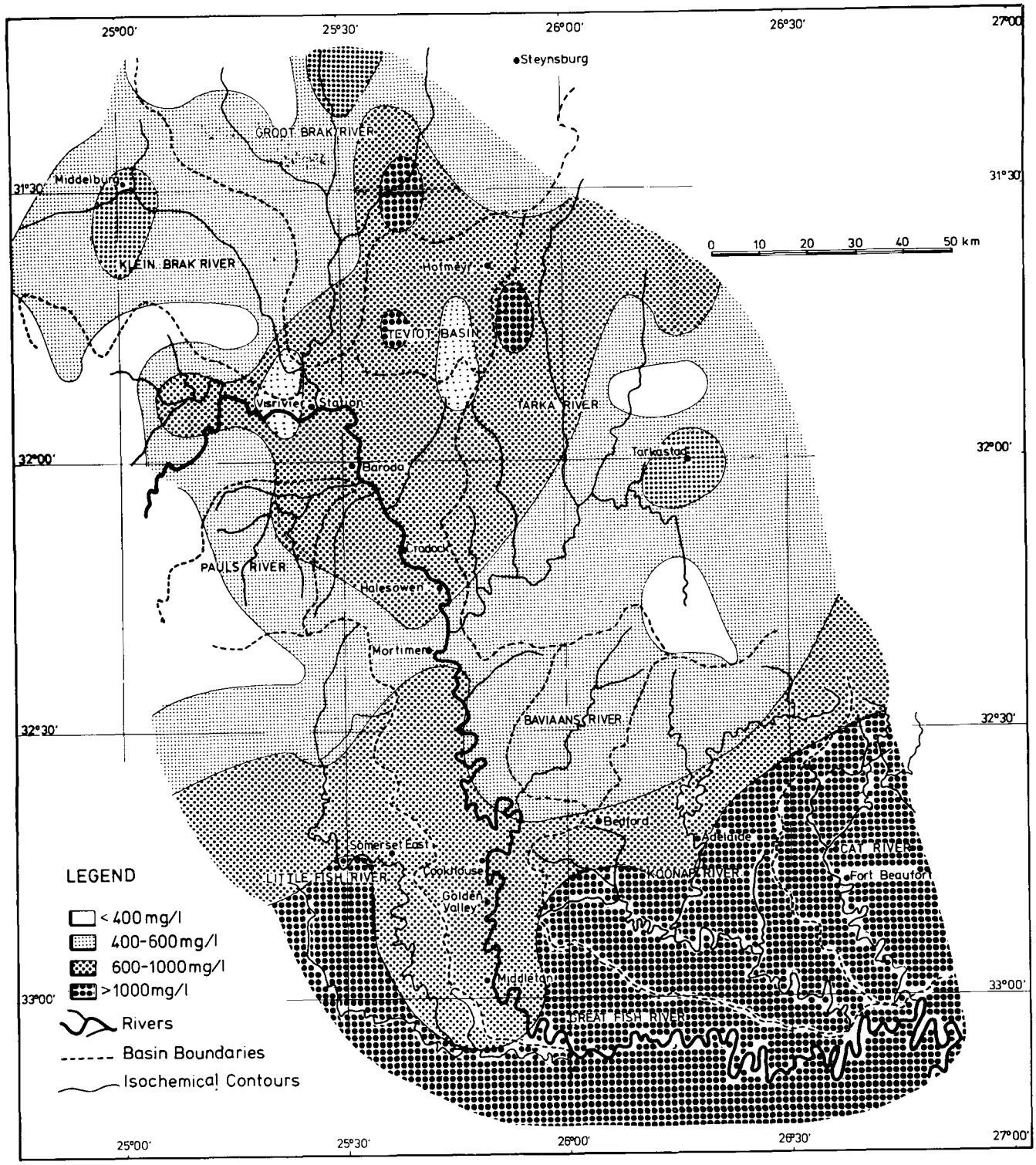

Figure 7
Isochemical contours of the total dissolved solids in the groundwater of the Great Fish River Basin.

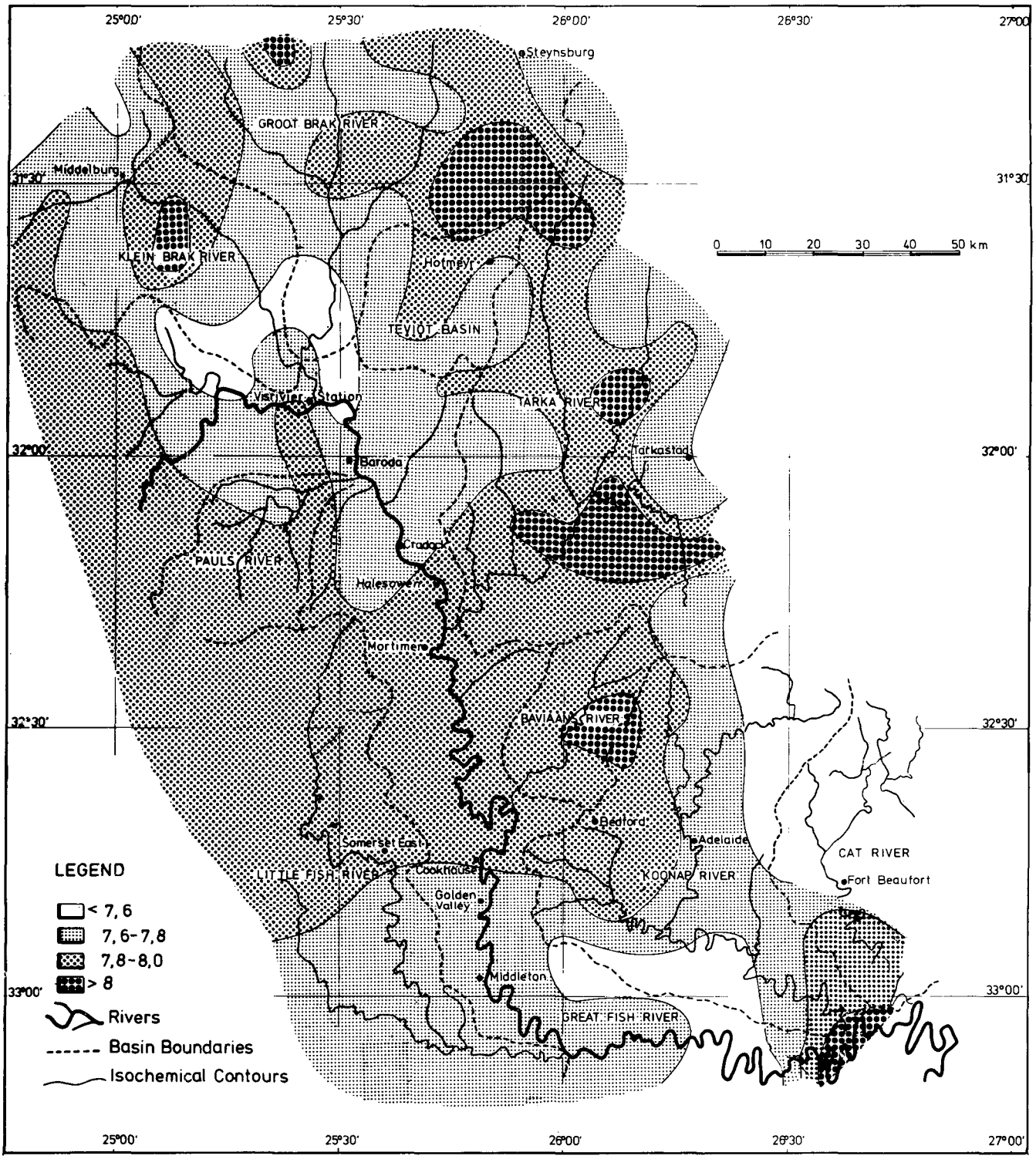

Figure 8
Isochemical contours of the hydrogen ion concentration (pH) in the groundwater of the Great Fish River Basin.

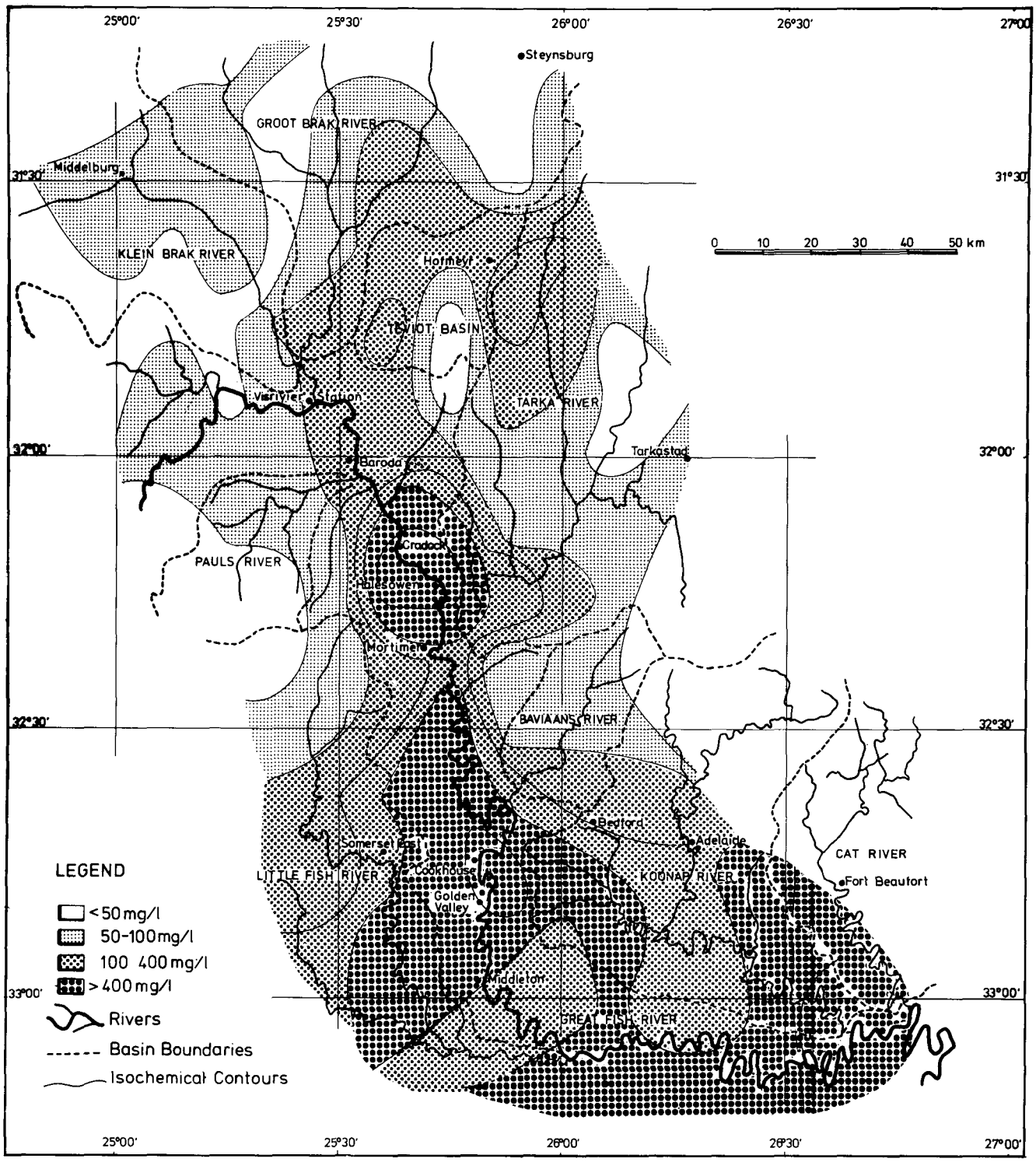

Figure 9
Isochemical contours of the sodium in the groundwater of the Great Fish River Basin.

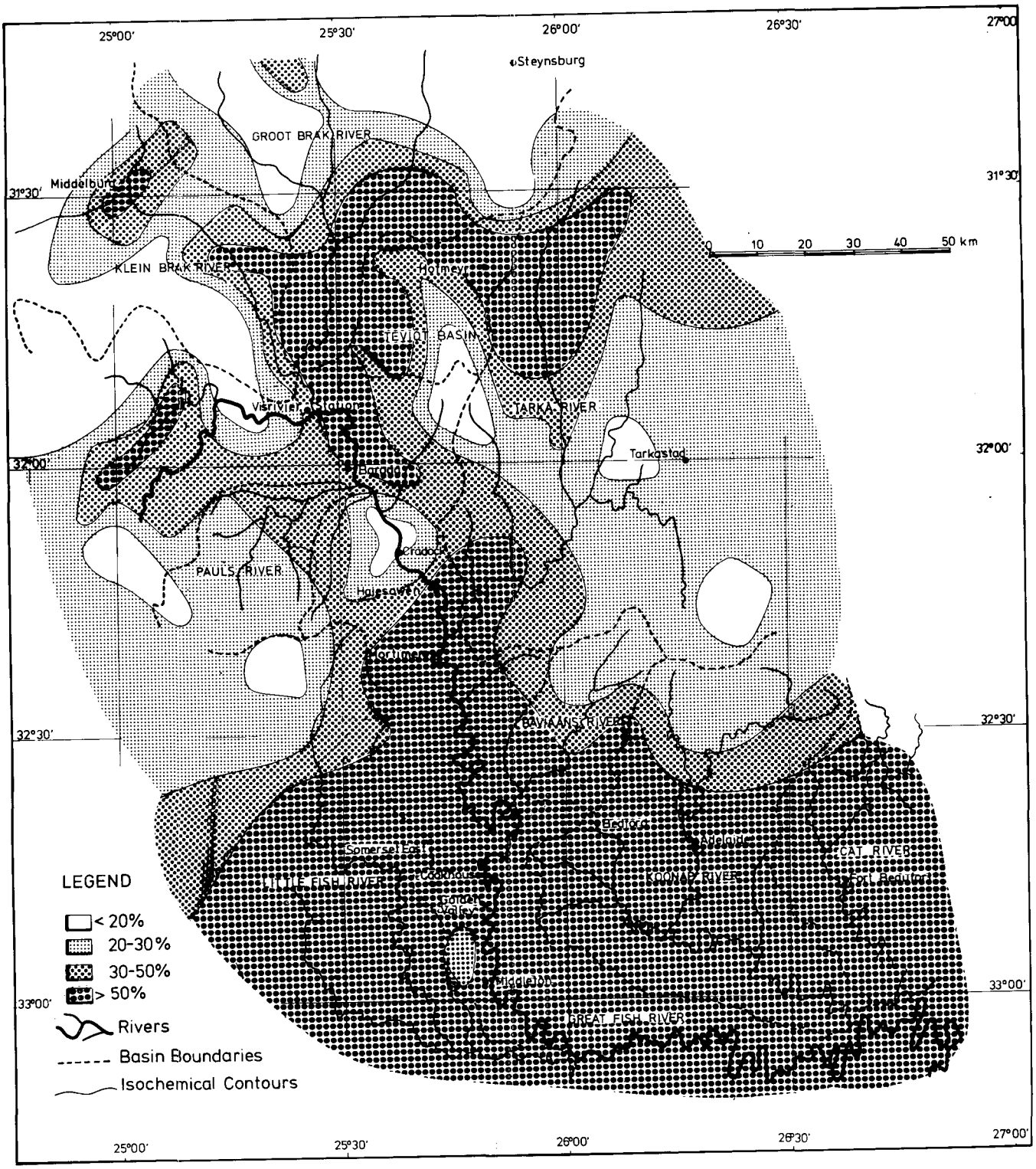

Figure 10
Isochemical contours of the percentage sodium in the groundwater of the Great Fish River Basin.

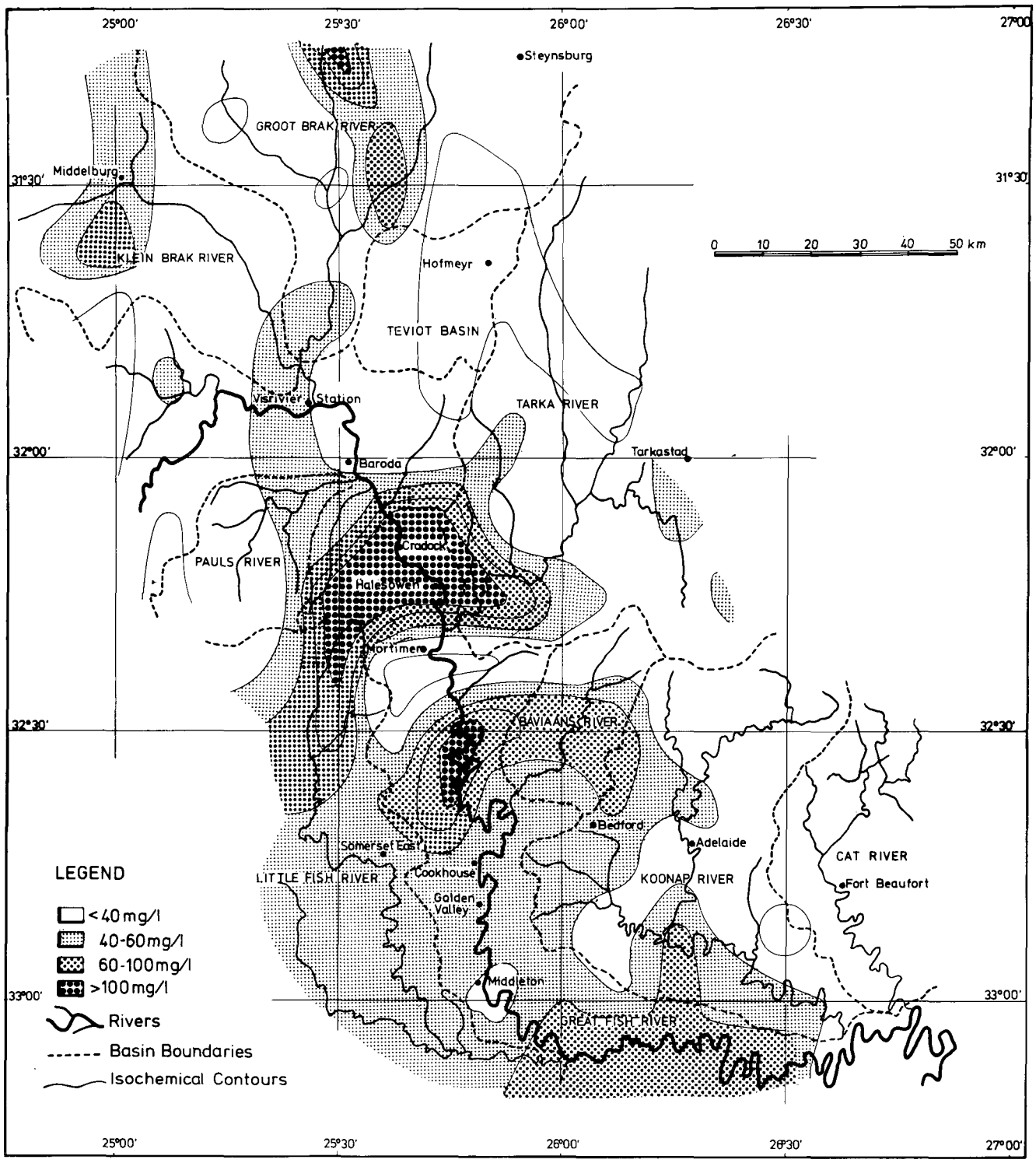

Figure 11
Isochemical contours of the calcium in the groundwater of the Great Fish River Basin.

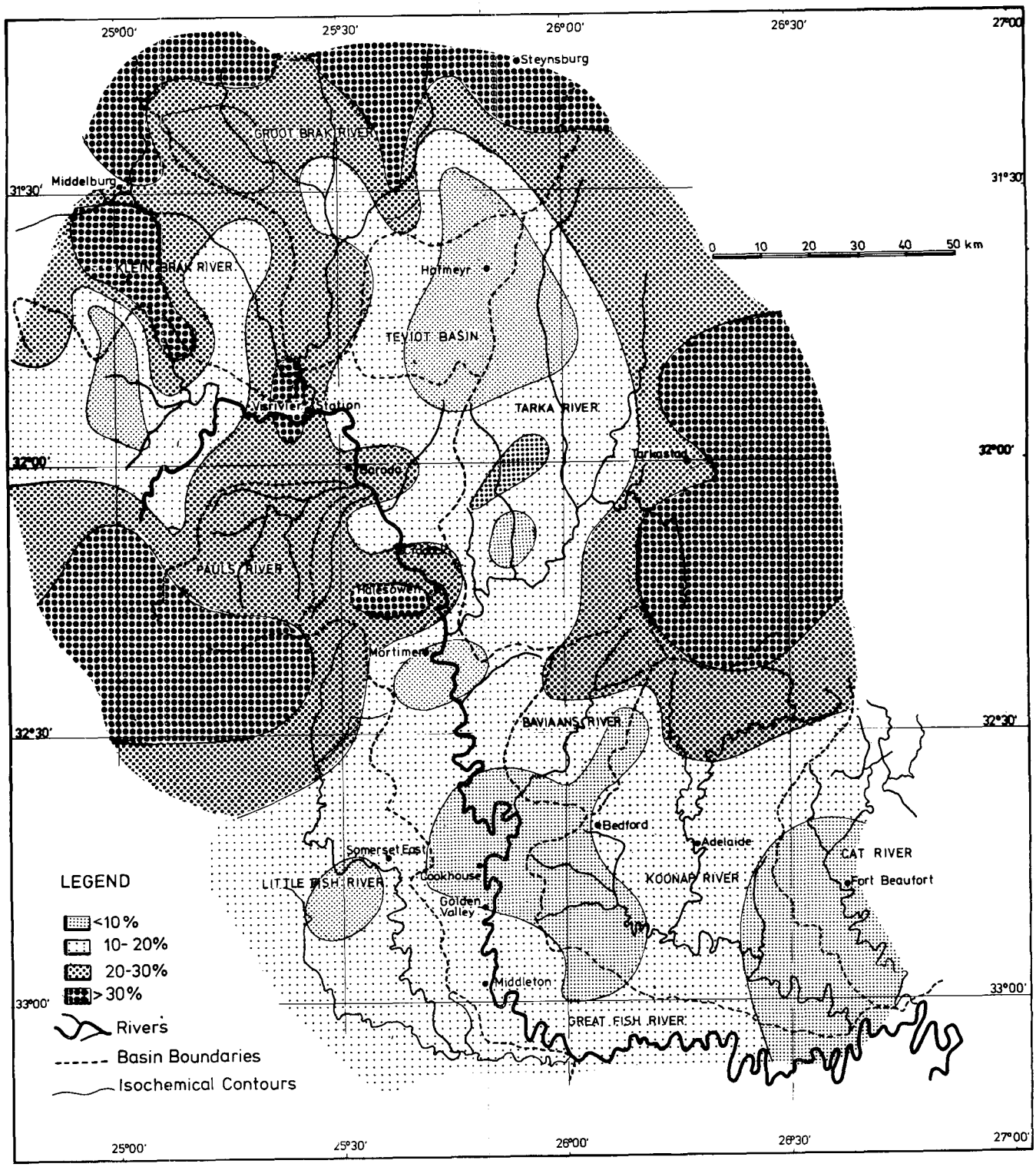

Figure 12
Isochemical contours of the percentage calcium in the groundwater of the Great Fish River Basin.

this ion (Fig. 12). Although the percentage of Ca^{++} in solution seldom exceeds 50 per cent of the total cations, the highest percentages, i.e. >30 per cent are encountered in the Interior Plateau and gradually decrease toward the centre of the Headbasin and the Marginal Region where values lower than 10 per cent are encountered.

Because of the above reasons Ca^{++} never occurs in the groundwater in any great concentrations (seldom exceeding 100 mg/ℓ) but nevertheless tends to follow the general trend of the concentration of TDS (Fig. 11).

It is interesting to note that in Fig. 11 the highest Ca^{++}-concentrations are encountered in the area around Cradock and Halesowen, where relatively pronounced deposits of calcrete and gypsum are found.

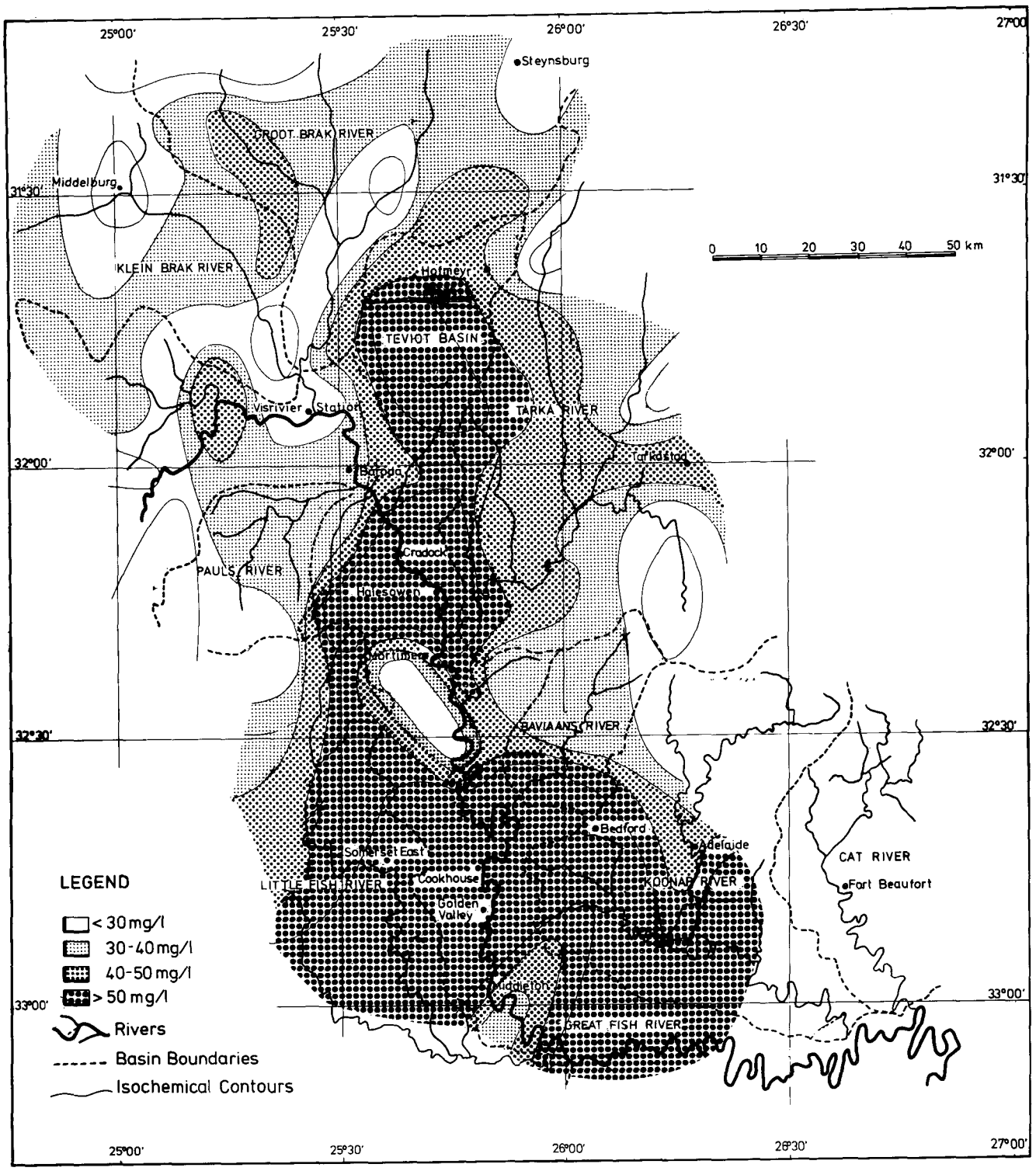

Figure 13
Isochemical contours of the magnesium in the groundwater of the Great Fish River Basin.

Magnesium

Although Hem (1970) is of the opinion that waters, in which magnesium is the predominant cation, are somewhat unusual, areas do occur in the Headbasin where Mg^{++} constitutes more than 50 per cent of the total cations in the groundwater (Fig. 14). It is quite clear that the higher percentages of Mg^{++} occur in the outer perimeter of the Headbasin, slightly farther down the flow-path of the groundwater than the calcium. This is because the magnesium is more mobile than the calcium, but less mobile than the sodium. Lower percentages of Mg^{++} are encountered in the central parts of the Headbasin where Na^{+} is the dominant cation.

The concentration of magnesium in the groundwater is generally very low, but tends to increase with an increase in total dissolved solids (Fig. 13).

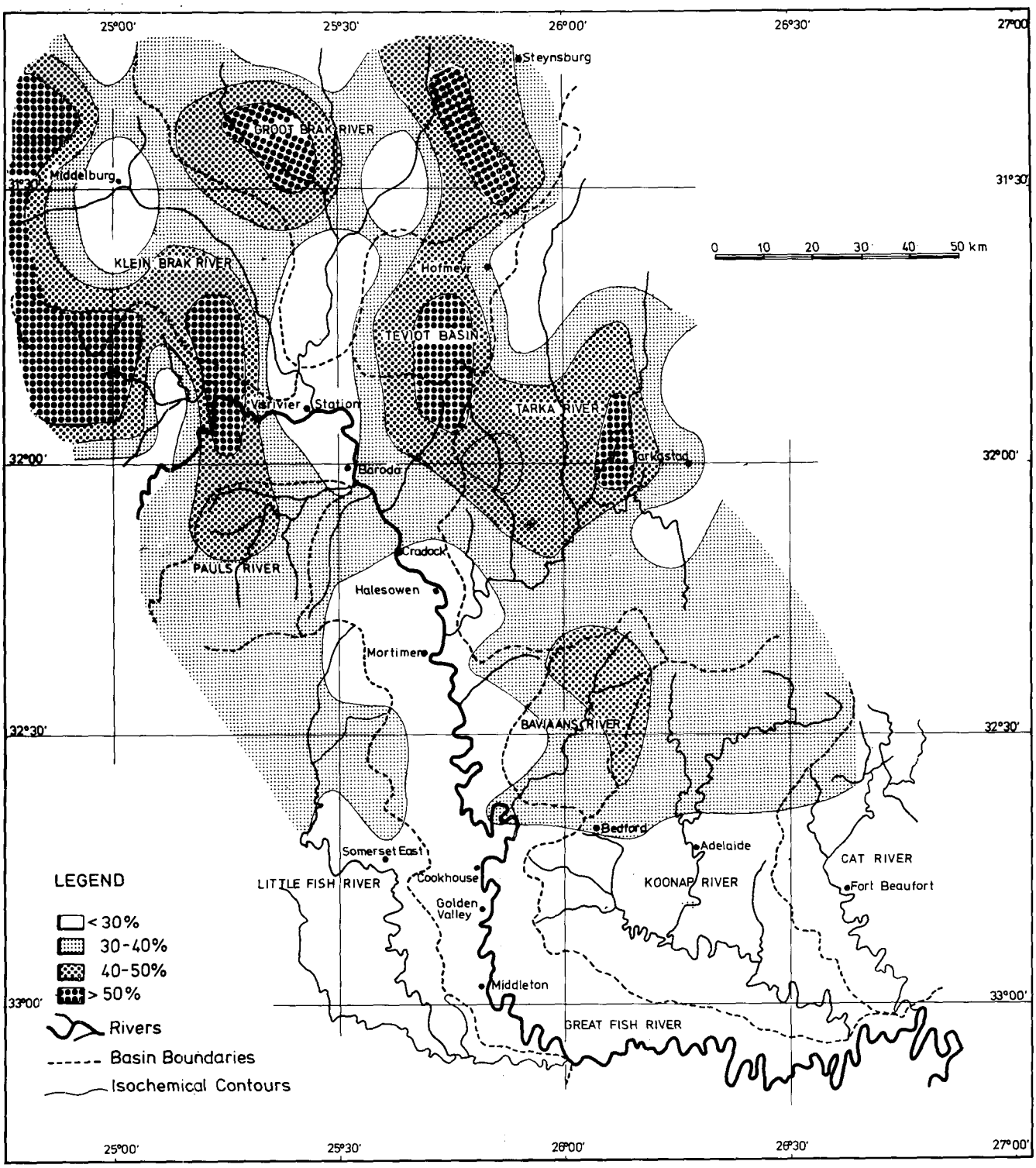

Figure 14
Isochemical contours of the percentage magnesium in the groundwater of the Great Fish River Basin.

As far as the soluble cations in the groundwater of the Great Fish River Basin are concerned, one may conclude that, without any exception all tend to increase in concentration with an increase in salinity. Calcium, however, is prominently the least mobile cation and dominates only in the Interior Plateau, while Mg^{++} is only slightly more mobile and Na^{+} is the most mobile. This trend is clearly expressed in Fig. 15 where the ratio of Na^{+} to $Ca^{++} + Mg^{++}$ is greater than one, mainly in the central part of the Headbasin and all the way down the river into the Marginal Region.

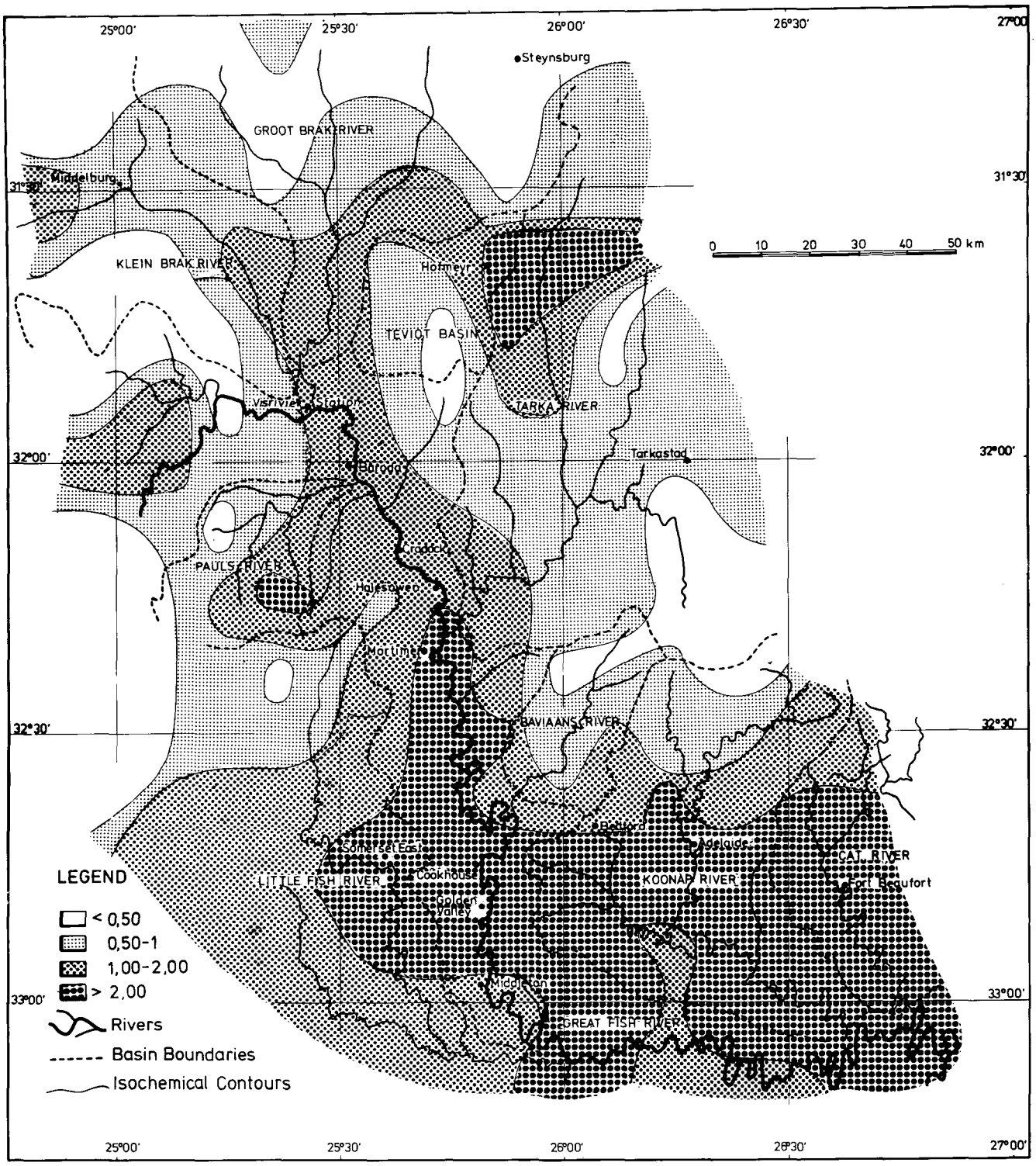

Figure 15
Isochemical contours of the cation ratio $\frac{Na^{+}}{Ca^{++} + Mg^{++}}$
in the groundwater of the Great Fish River Basin

Chloride

A brief discussion on the geochemical behaviour of chloride is necessary before actually investigating the concentration of this ion in the groundwater of the various geomorphologic environments.

Chloride ions do not significantly enter into oxidation or reduction reactions, they form no important solute complexes with other ions (especially in dilute aqueous solutions), do not form salts of low solubility, are not significantly adsorbed on mineral surfaces and play few vital biochemical roles (Hem, 1970). It may be deduced therefore that the circulation of Cl^{-} in

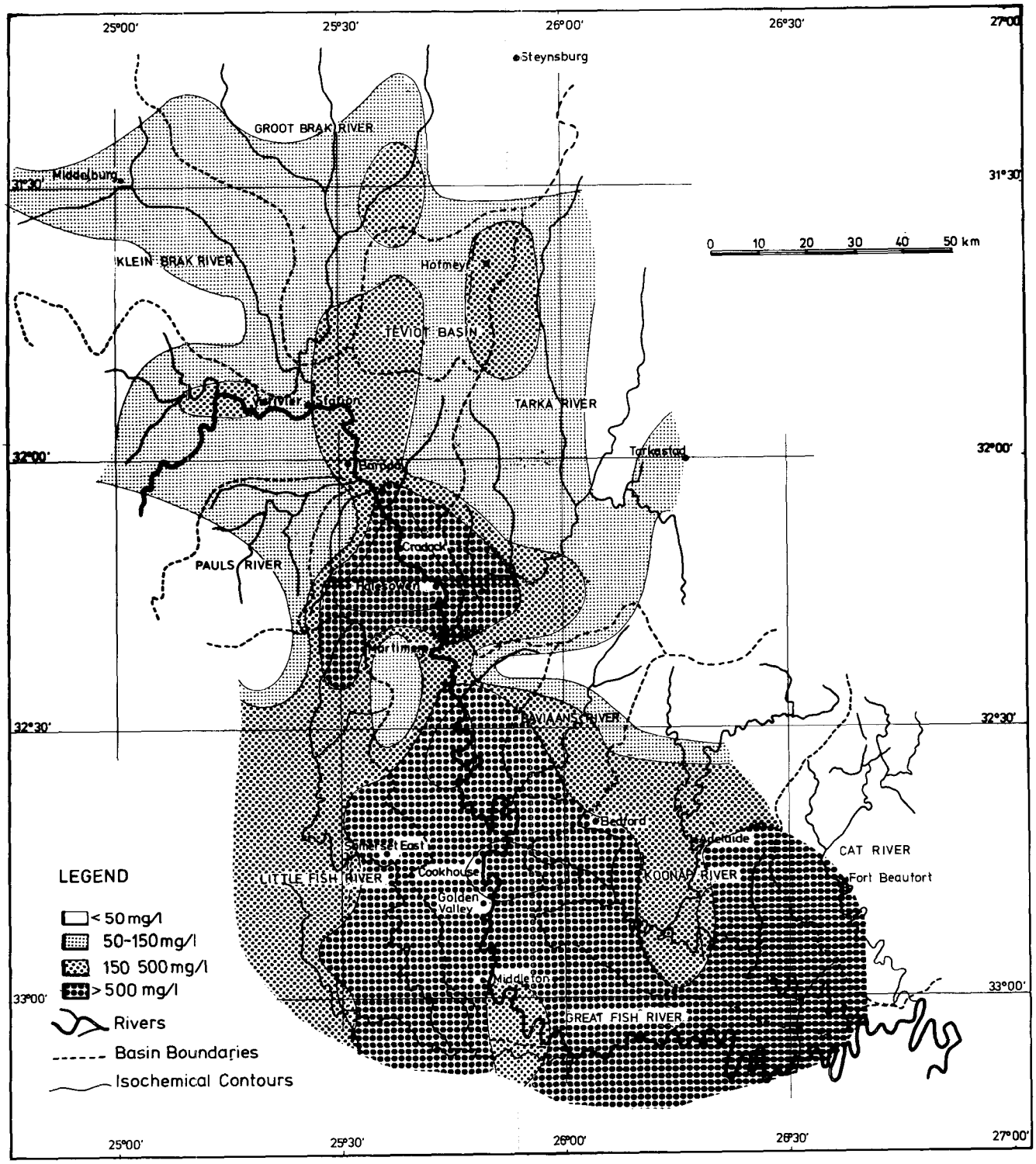

Figure 16
Isochemical contours of the chloride in the groundwater of the Great Fish River Basin.

the hydrological cycle is largely through physical rather than chemical processes.

The chloride ions therefore tend to remain in solution and are able to withstand most of those processes which reduce the concentration of other ions. Chloride concentrates in groundwater close to the surface, as a result of evapotranspiration, but can also concentrate in deepseated connate waters as a result of ultra-filtration by fine-grained argillaceous sediments during compaction (Degens and Chilingar, 1967).

There is a marked increase in the actual concentration of chloride, as well as in the percentage chloride of the total anions, in the groundwater as it proceeds towards the centre of the Headbasin (Figs. 16 and 17). This trend can also be observed toward the Marginal Region, but of great interest is the nar-

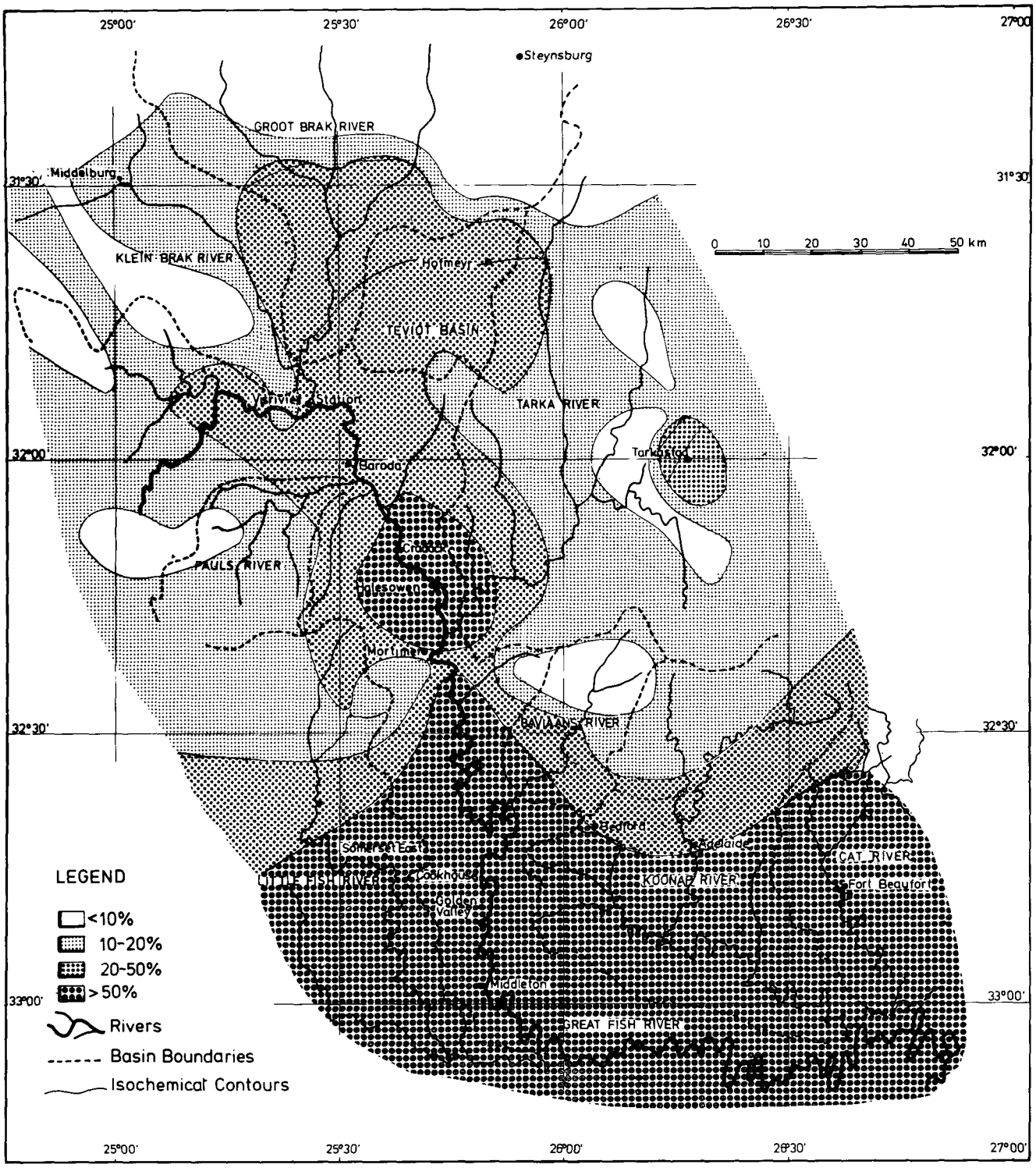

Figure 17
Isochemical contours of the percentage chloride in the groundwater of the Great Fish River Basin.

rowing immediately south of Mortimer. Such a narrowing may be attributed to the presence of some form of hydrological barrier in the area and is displayed by most of the other soluble constituents. Such a barrier naturally retards the rate of groundwater flow, thus increasing the residence time in the environment. This area marks the lower end of the Headbasin where the river cuts through the Great Escarpment.

A similar trend to that of Na^+ is revealed by the Cl^-, which agrees with the statement by Hem (1970) that the most common type of water in which chloride is the dominant anion, is one in which sodium is the predominant cation.

The higher concentration of chloride in the groundwater of the Marginal Region may partly be attributed to the retention of Cl^- during the upward migration of the oceanic connate

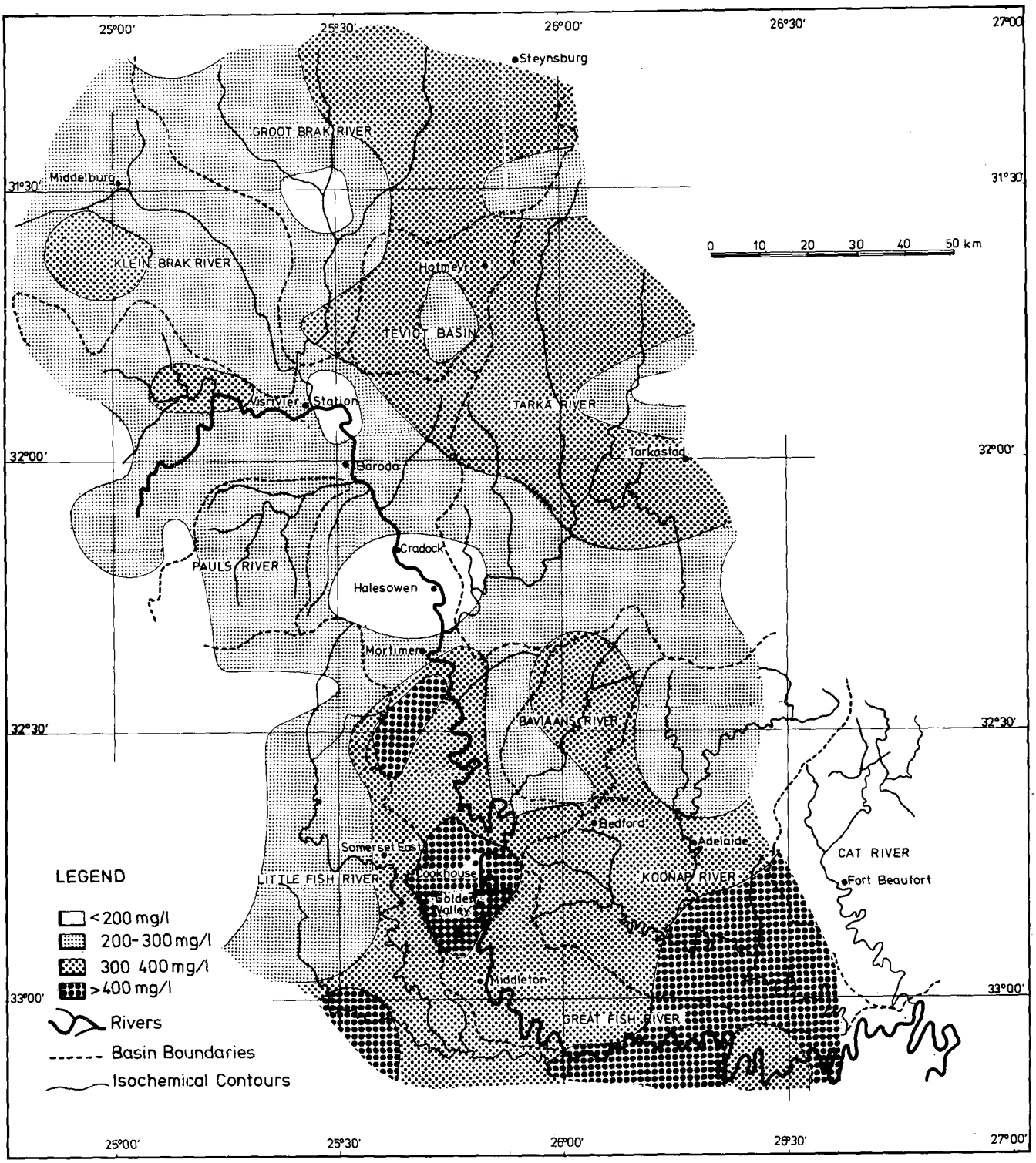

Figure 18
Isochemical contours of the alkalinity (HCO_3^-) in the groundwater of the Great Fish River Basin.

water as a result of compaction of the sediment.

As in the case of the Na^+, the possibility of an atmospheric source cannot be ruled out.

Alkalinity

Hem (1970) is of the opinion that the alkalinity of many streams is caused mainly by the solution of CO_2 of the atmosphere, rather than from the rocks of a drainage basin. Where this is the case low Ca^{++} or Mg^{++}-concentrations must, however, be encountered as these ions are produced mainly by the $CaCO_3$-hydrolysis reaction.

It is therefore clear that the alkalinity in groundwater may originate from two sources, i.e.:

(i) The hydrolysis of $CaCO_3$:

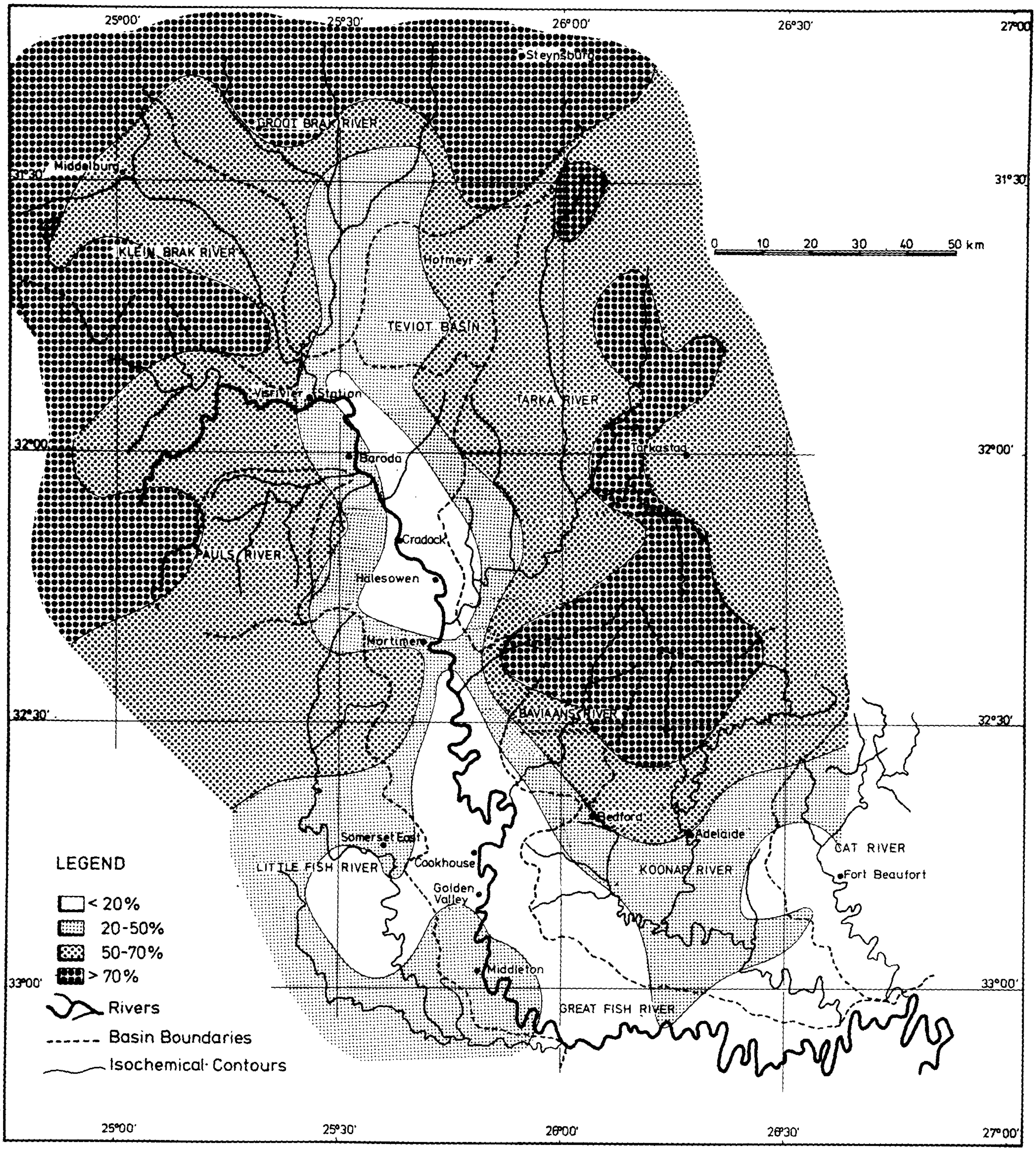

Figure 19
Isochemical contours of the percentage alkalinity (HCO_3^-) in the groundwater of the Great Fish River Basin.

$CaCO_3 + H_2O \rightleftharpoons Ca^{++} + HCO_3^- + OH^-$,
In this case the Ca^{++}-concentration, alkalinity and pH are high.

(ii) The solution of CO_2 from the atmosphere or from biological action:

$H_2O + CO_2 \rightleftharpoons H_2CO_3$
$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$
$HCO_3^- \rightleftharpoons H^+ + CO_3^=$

In this case no Ca^{++} is produced and although the alkalinity increases, the pH clearly decreases.

In the Great Fish River Basin there appears to be quite a good correlation between the alkalinity (Fig. 18) and the pH (Fig. 8). The most striking coincidence is that in the Interior Plateau the pH is high with a relatively high alkalinity, thus suggesting the hydrolysis of $CaCO_3$. In the Marginal Region high alkalinity concentrations are encountered, whilst the pH ap-

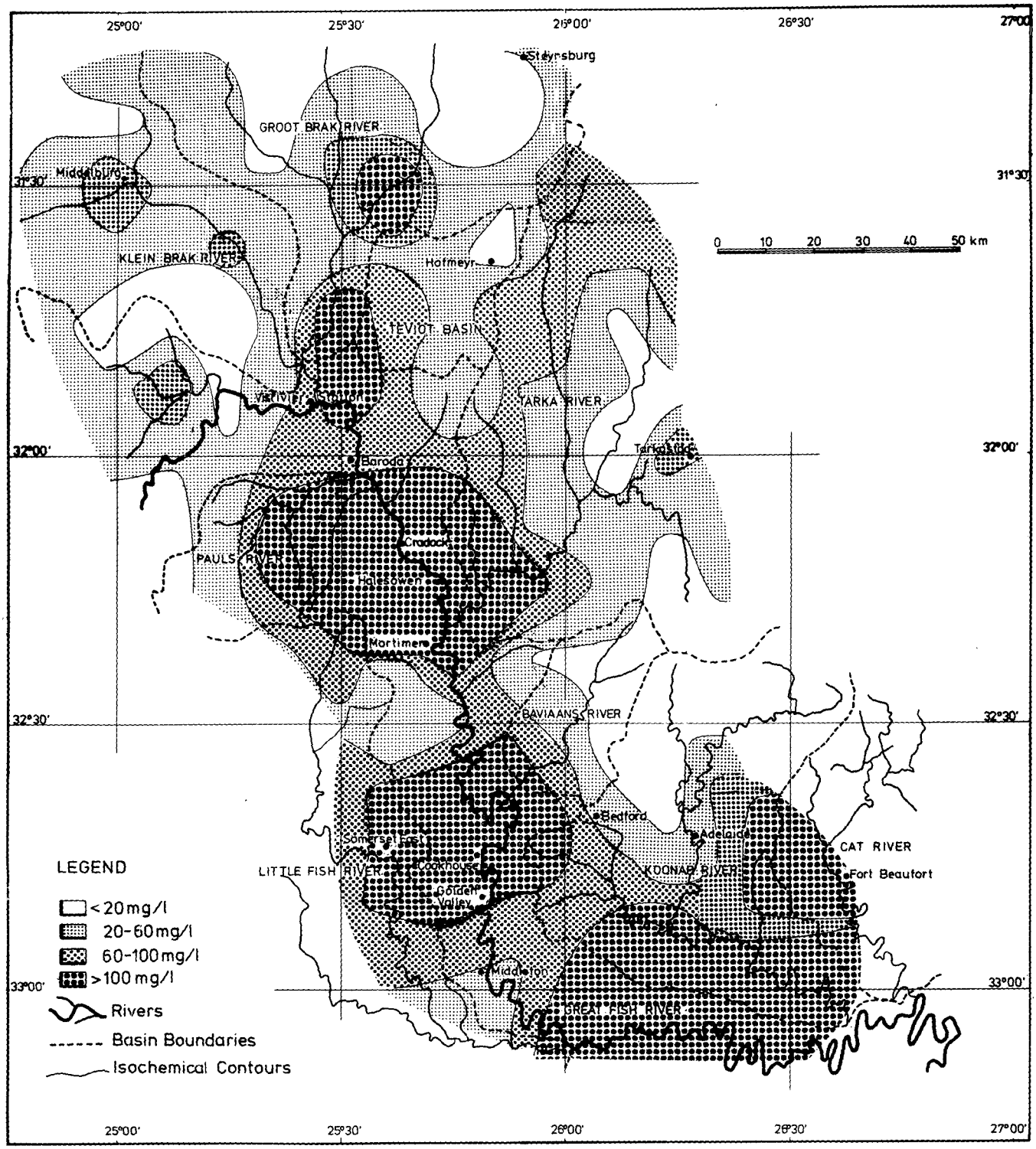

Figure 20
Isochemical contours of the sulphate in the groundwater of the Great Fish River Basin.

pears to be relatively low. This suggests that most of the HCO_3^- in this area is due to the mere solution of CO_2 in the groundwater.

Whilst the actual alkalinity of the groundwater in the area appears to occur in irregular concentrations (Fig. 18), the percentage alkalinity of the total dissolved anions reveals a regular trend in which the alkalinity appears to decrease along the flow direction of the groundwater (Fig. 19). The highest alkalinity percentages (>70 per cent) occur in the Interior Plateau, whilst percentages exceeding 50 per cent also occur over a large section of the outer perimeter of the Headbasin. High alkalinity percentages are also encountered in the groundwater of the Great Escarpment. Only a small section of the central part of the Headbasin and the whole of the Marginal Region contain groundwater in which the alkalinity is less than 50 per cent of the total anions in solution.

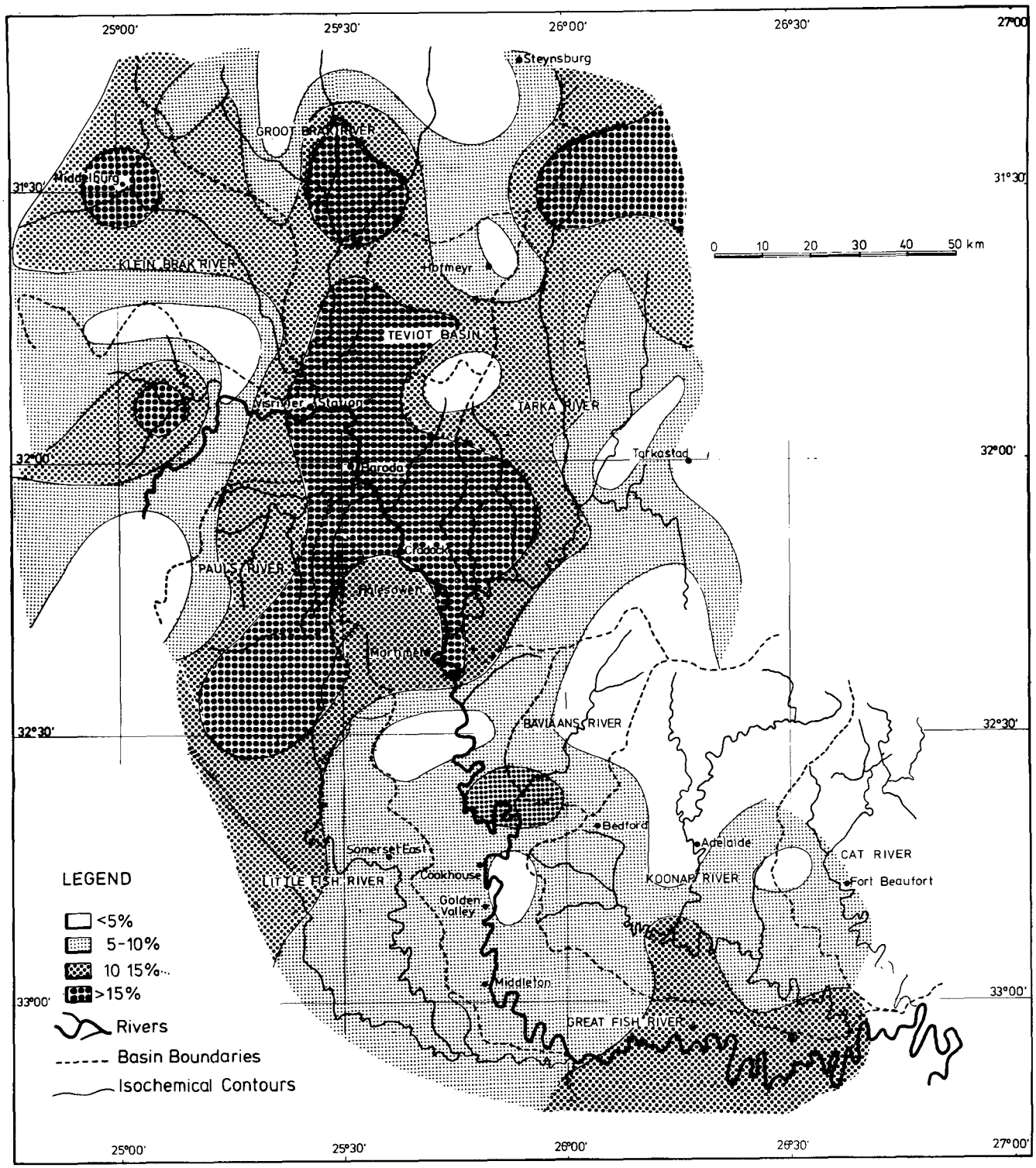

Figure 21
Isochemical contours of the percentage sulphate in the groundwater of the Great Fish River Basin.

This trend is very similar to that of the calcium (Fig. 12). It may therefore be deduced that the concentration of Ca^{++} in the groundwater over large parts of the area is controlled mainly by the equilibria of the carbonate in the water, or that the alkalinity is controlled mainly by the solution of $CaCO_3$ in the water.

Sulphate

The sulphate ion is chemically stable in aerated water and forms salts of low solubility with only a few metals (Hem, 1970). He also states that most shales and fine-grained sediments, which

are freshly raised above sea level, are exposed to the natural processes of weathering which bring about oxidation within the aerated zone, right down to zones below the water table. During such processes, sulphate is produced which may be transported away from the source. The rate at which the sulphate is removed, depends on the runoff rate and is therefore greatly dependent on environmental factors such as climate and topography.

In semi-arid environments such as those encountered in large areas of the Great Fish River Basin, the supply of solutes is relatively large in proportion to the water volume in which it can be carried away and therefore where the subsurface drainage is poor, an accumulation of dissolved solids occurs with $SO_4^=$ as one of the constituents.

Figure 20 proves that there is a pronounced migration of $SO_4^=$ from the high lying Interior Plateau to the lower lying central parts of the Headbasin. There also appears to be a further migration of sulphate from the Great Escarpment to the Marginal Region.

Sulphate, however, constitutes only a small percentage of the total anions in the groundwater and only in a limited portion of the Headbasin does this ion ever exceed 15 per cent of the total dissolved anions (Fig. 21).

Discussion and Conclusion

On the grounds of the above data, it appears that the macrotopography of the Great Fish River Basin plays a large role in controlling the migration and accumulation of ions in the groundwater.

Low salt concentrations are encountered in the groundwater of the higher lying Interior Plateau where relatively free circulation and leaching occurs. In contrast to this, higher salt concentrations are encountered in the lower lying Headbasin and Marginal Region where stagnant conditions prevail.

The pH of the groundwater is also influenced by the topography of the area. Hydrolysis reactions involving the solution of $CaCO_3$ in the Interior Plateau are responsible for higher pH values in this area, whilst lower pH values are encountered in the lower lying areas. More conspicuous, however, is the fact that Ca^{++} and HCO_3^- are the predominant ions in the groundwater of the Interior Plateau, whilst Na^+ and Cl^- in turn dominate the groundwater of the lower lying regions. The reason for this phenomenon is attributed to the fact that meteoric water in the Interior Plateau is able to dissolve $CaCO_3$, but as this water percolates down toward the lower lying regions, it becomes saturated with Ca^{++} and HCO_3^- so that $CaCO_3$ is precipitated as calcrete. Calcium may furthermore be removed from the solution by means of exchange for adsorbed Na^+ on clay particles through which the water flows. The buildup of Na^+ and Cl^- as the predominant ions in the groundwater of the Headbasin and Marginal Region is therefore to be expected.

There appears to be a marked difference between the chemical character of the groundwater of the Marginal Region and that of the other geomorphologic regions. This difference is caused by the extremely high percentages of Na^+ and Cl^- in the groundwater of the former region; a phenomenon which may be attributed to the influence of saline connate water from the sedimentary rocks of the Dwyka Formation and Ecca Group in the region. The possibility of Na^+ and Cl^- being concentrated in the Marginal Region by atmospheric processes cannot be ruled out, but further research in this field is necessary to prove or disprove it.

Magnesium and sulphate, which have intermediate mobilities, tend to concentrate in the groundwater somewhere between the two extremes mentioned above. This tendency is noticed especially with Mg^{++}, whilst the $SO_4^=$, with a slightly greater mobility under the prevailing conditions, is often concentrated with Na^+ and Cl^- in the groundwater.

Acknowledgements

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