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CSIRO Land and Water, Private Bag, Wembley. W.A. 6014

and

A. Knapton

Department of Exploration Geophysics, Curtin University of Technology,
Bentley. W.A. 6102

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HYDROGEOMORPHOLOGY AND HYDROGEOLOGY OF THE UPPER KENT RIVER CATCHMENT AND ITS CONTROLS ON SALT DISTRIBUTION AND PATTERNS OF GROUNDWATER DISCHARGE

R.B. Salama[1], G.A. Bartle [1], L. Ye [1], D.R. Williamson[1], G.D. Watson[1] and A. Knapton [2].
[1] CSIRO Land and Water, Private Bag PO, Wembley. WA 6014.
[2] Department of Exploration Geophysics, Curtin University, Bentley. WA 6102

ABSTRACT

To develop an integrated catchment management plan for the Upper Kent River catchment in south-west of western Australia requires the integration of several kinds of data sets ranging from the biophysical to socio-economic data. A major concern in this region is salinisation - why is it occurring, how far it will spread and how can it be managed. One key component of the biophysical information needed to address salinity issues is hydrogeology, and in particular mapping the similar hydrogeomorphic units which can be hydrological and hydrogeological related. To achieve this objective we have developed a new explicit technique for mapping hydrogeomorphological units (HGU). These units are used as surrogates for classifying the catchment into areas of similar hydrogeological characteristics which will have similar salinity patterns. The results of the classification were compared with the traditional geophysical and hydrogeological methods. HGUs are based on geology, vegetation and slope characteristics. The determination of discharge areas is based on the relationship between hydrogeomorphologically controlled groundwater levels and the surface topography.

The distribution of HGUs in the catchment is controlled by the weathering characteristics of each of the geological formations on which they are developed. As a result flats developed in the metasediments in the eastern part of the catchment. Lakes developed along depressions created by the fault systems. Gently undulating hills developed in the northern granitic areas of the Yilgarn Craton, while rugged undulating hills developed on the gneissic rocks of the Albany Fraser.

The regional pattern of groundwater movement indicates that groundwater moves from the high undulating areas towards the lowland. Groundwater discharge is assumed to take place as a function of slope, break of slope and curvature. The distribution of the water-level contours indicates that groundwater is stagnant in the flat areas of the landscape. Groundwater levels are deep in the undulating country, near the surface in all flat and morass areas of the landscape and depth to water decrease by decreasing elevation.

The results of the analysis of the cored holes, the downhole apparent conductivity, the surface EM and the airborne EM indicate that salt storage is high in the morass, flats and lowland areas of the landscape. Salt storage decreases with an increase in elevation and in slope.

The newly developed methods were used to prepare water level maps for the Upper Kent River catchment, and using past water level trends, different scenarios of water level rise were used to predict water level trends to the year 2010. The same techniques were also used to predict areas prone to inundation.

The results shows that with the worst possible scenario of a rise of 2 m in the high land and 1 m in the lowland, water levels in 65% of the catchment will be less than 2 m. With a rise of 2 m in the low lands and 1 m in the high lands only 47% of the catchment will have water levels less than 2m.

This shows that it is very important to control the rise of water levels in the high lands, where the water levels trends indicate continuous rise. Although draining the lowlands will reduce the water levels, if nothing is done to the highlands, a higher proportion of land will be affected.

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INTRODUCTION

The National Dryland Salinity Research, Development and Extension Program, NDSP, (LWRRDC, 1994) aims to collaboratively develop ways of approaching dryland salinity management through coordinating the various resources allocated to research, development and extension. It aims to develop generic tools of national significance and the means to extend and apply this knowledge and its resulting technologies to other catchments around Australia. One catchment in each of 5 states has been selected for the national program. The five catchments have been selected on the basis that each highlights different salinity management issues of importance.

The Kent River Catchment is located in the south-west corner of Western Australia where there is a high agricultural development potential. It has been selected as the focus catchment in the southwestern region of Australia's agricultural lands. The Kent River also has the off-site dimension of potential potable water supplies, if the salinity problems caused by the increase in saline groundwater discharge following clearing can be arrested and reversed. Due to the higher rainfall(>500 mm annual) in the catchment compared to the wheatbelt of Western Australia, there is the prospect of commercial tree plantations and agroforestry variations using both local and imported eucalypt species.

The design of catchment rehabilitation programs to limit the resource degradation problems of water logging and inundation, rising water tables and pressures, non-irrigated land and stream salinity and soil erosion require the integration of management for both cause and effect of these problems. The vast areas through which these catchments are distributed across the southern half of the Australian continent, along the different climatic zones, geological boundaries, hydrological basins and vegetation types, makes such studies nearly impossible to conduct using routine hydrogeological methodology at the level of accuracy required to reduce uncertainty. Therefore, the hydrogeological level of research must be kept to a minimum and surrogates found to complement or induce this research (Salama, 1994a&b).

The level of hydrogeological knowledge of the system is associated with several levels of uncertainty, related to the catchment boundaries and the different hydrogeological characteristics of the catchment (types of aquifer, lithology, stratigraphy, hydraulic properties including saturated hydraulic conductivity, transmissivity, porosity and specific yield) (Freeze et al., 1990; Peck et al., 1988). The level of knowledge is also related to the geological and structural controls of the catchment (Salama et al, 1994a), together with the hydro-geochemical and geophysical parameters of the solutes, and the geological material within which the catchment is contained (Salama et al, 1993c & d).

As one of the five national program focal catchments, the Kent Catchment has provided an opportunity for new methodologies to be developed for landscape mapping, hydrogeomorphic classification and hydrogeological characterisation. Detailed knowledge of these features is basic to development of management practices to control surface water and groundwater movement. It was therefore essential that some of the well-established traditional research methods in the areas of hydrological and hydrogeological data collection and collation procedures (for example, Australian Soil and Land Survey Handbook Vol, 1 (McDonald et al, 1990), Vol 2 (Gunn et al, 1988) and Vol. 3 (Rayment and Higginson, 1992)) would be used for comparison with the new methods. Although comparison is made with these traditional methods, it must be remembered that the results from the traditional methods are questionable, as they are often based on small scale geological maps, few drilled boreholes, and water level measurements which, in most cases, are tapping different types of aquifers and measured at different times of the year.

Beginning in 1990, the CSIRO Division of Water Resources (now part of CSIRO Land and Water), together with other state agencies in Western Australia; the Department of Agriculture, the Department of Land Conservation and Management, the Water Authority of Western Australia and the Hydrogeology Section of the Department of Mines, and supported by the Kent River Land Conservation District Committee, developed a coordinated and integrated research program for the rehabilitation of the Kent River catchment and future restoration of the river as a potable water resource. The program included 6 projects examining catchment characterisation, hydrology and hydrogeology, vegetation options, socioeconomic analysis, remediation strategies and the implementation of appropriate management. The CSIRO Division of Water Resources, with the support of the CSIRO Institute of Natural Resources and Environment, carried out the study reported here as part of the catchment characterisation component in the program. Development of the technology within the framework of a Geographic Information System (GIS) was continued as one of the activities in LWRRDC Project DAW16 following the establishment of the Kent Catchment as a focus catchment in the National Dryland Salinity R, D&E Program in 1993 (LWRRDC, 1994).

This report outlines the detailed hydrogeomorphological, hydrogeological and associated studies carried out in the Upper Kent River catchment by CSIRO and compares the results of the traditional methods with newly developed methods. This technology had its initially development as an integral part of these studies within the Kent Catchment, and the results of the subsequent, more rigorous, development have been published in Salama and Hatton (1998a, b). Specific attention is given to the source and management of excess water in the catchment and to the relationship of the hydrogeomorphology to the distribution of stored salt.

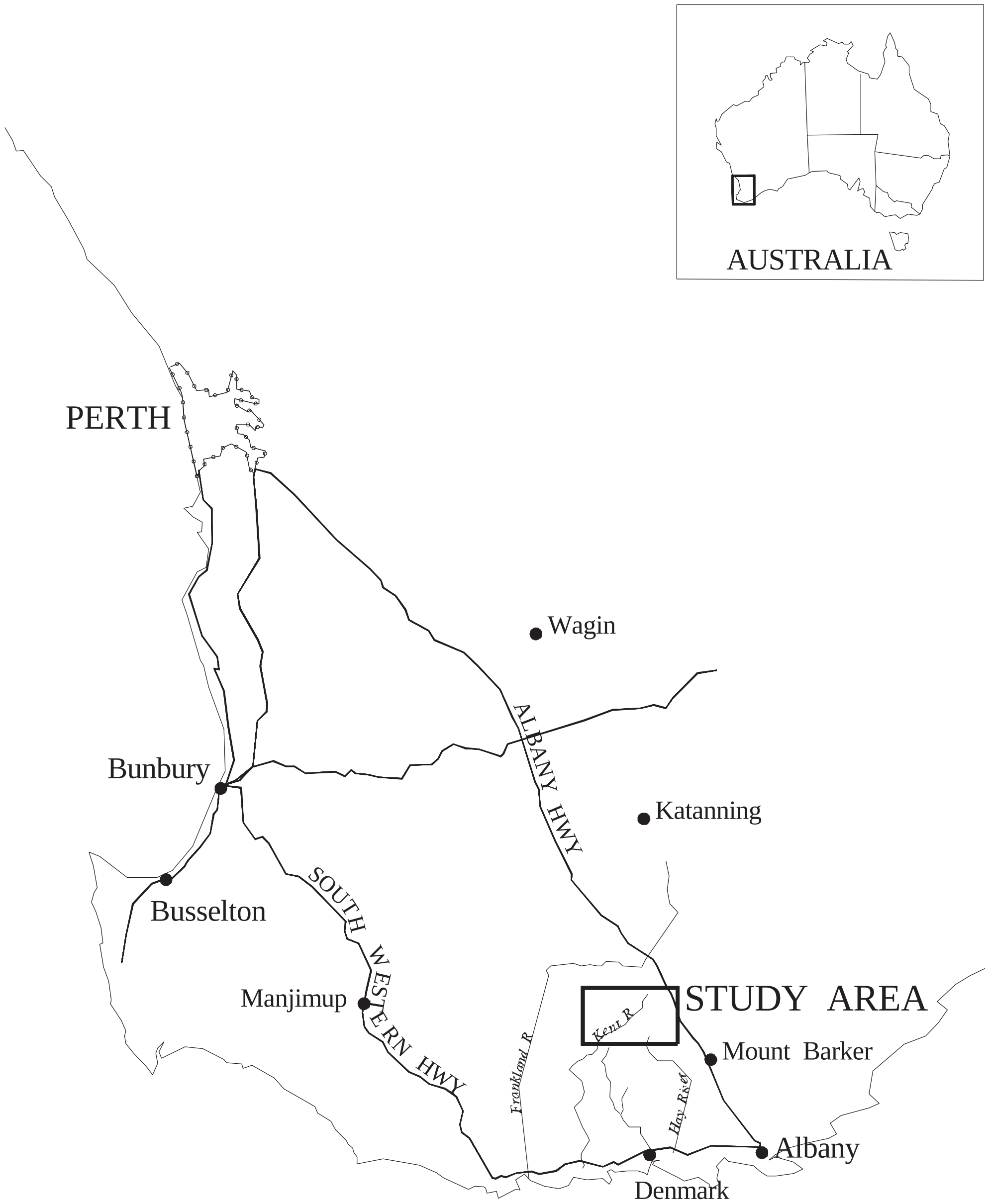


Figure 1: The location of the Kent River Catchment in the south-west of Western Australia

OVERVIEW OF THE KENT RIVER CATCHMENT

The Kent River Catchment (Basin 604) is located in the southwest of the Australian continent between latitudes 34°18' and 35°04' and longitudes 116°48' and 117°34'with an area of about 2170 km^2. (see Figure 1) The Kent River drains westward from headwaters in the north-east near the Albany Highway at Tenterden, then curves southward near Rocky Gully and, after being joined by the Styx River, flows on into the Owingup Swamp and reaches the Southern Ocean through the Irwin Inlet. The catchment is located within the Shires of Cranbrook, Plantagenet and Denmark.. The development of agriculture has occurred primarily in the upper half of the catchment with the majority of the southern half remaining forested. Collins and Fowlie (1981) gave the private land tenure in the catchment as 57% with 39% cleared for agricultural use. Alienation of crown land ceased in 1961 to protect the surface water resources. Legislation to control clearing in order to minimise further deterioration of water quality was enacted in 1978.

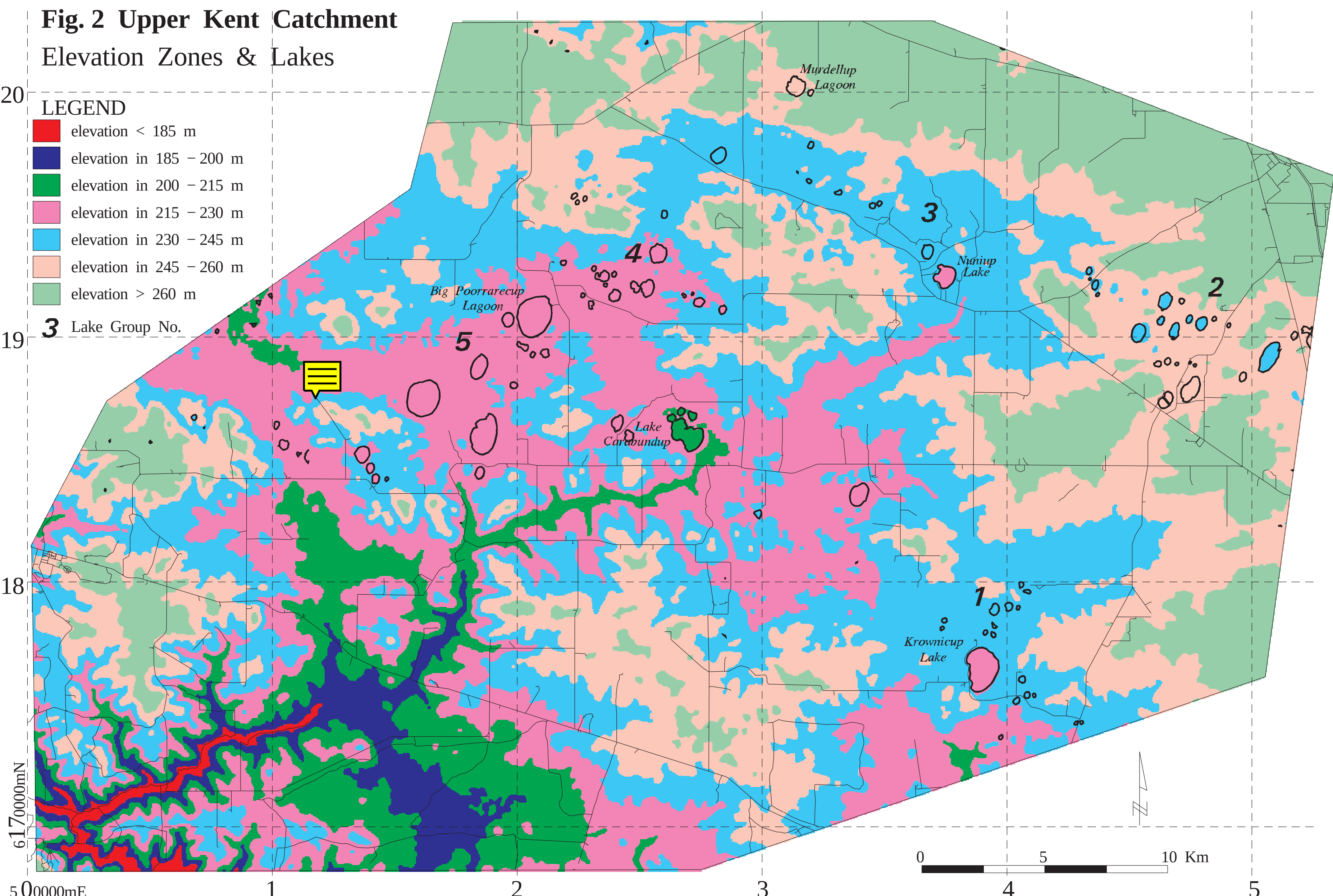
The Upper Kent River Catchment is about 1135 km^2 to stream gauging station 604001 located about 12 km south of Rocky Gully. This sub-catchment has no rural urban centres but supports 112 farms in a mediterranean type climate with a mean annual rainfall of 550 to 900 mm and a pan evaporation of 1350 mm yr^{-1}. The geomorphology is of low to moderate relief, including a gently undulating plateau with outcropping hills, and bauxitic soils overlying granitic rock. Based on landform and soil classifications, 44% is a dissected plateau of rolling country with yellow mottled soils and some gravels, 27% is swampy flats, drainage lines and lake depressions with leached sands and podzolic soils, 23% is lateritic plateau in uplands with sands and ironstone gravels over mottled clays, and 6% is incised valleys with moderate slopes having yellow podzolic soils and red earths (from Atlas of Australian soils as summarised in Public Works Department, 1984).

Clearing of native vegetation started in the Upper Kent catchment in the mid 1800s. The major alienation of crown land occurred in the 1920s. After the Second World War large-scale clearing commenced as part of the Land Settlement Scheme with about 25% cleared by the 1950s increasing to 55% by 1965 (Collins and Fowlie, 1981). By the time clearing controls were established in 1978 about 65% of the sub-catchment had been cleared of natural vegetation primarily for purposes of sheep and cattle grazing, though farm forestry emerged in the late 1980's as an economic alternative and is now increasing in extent. Also in the mid 1980's, the poor economic position of the wool industry encouraged development of cereal cropping which now occupies about 15% of agricultural land, with expectation that this will increase. About 27% of the sub-catchment supports varying quality of remnant vegetation on alienated land. The remaining 8% is forest reserve, national parks and conservation reserves.

The stream water quality showed an annual increase in salinity of 52 mg L^{-1} (TDS) over the period 1956-86 (Schofield et al 1988). The present flow-weighted salinity is of order 2000 mg L^{-1}. Land degradation problems included permanent and seasonal waterlogging with the whole catchment classified as prone to seasonal waterlogging. Of the cleared non-saline land in the Upper Kent sub-catchment, 25% is severely waterlogged and a further 25% moderately affected between May and October. An additional 10 to 15% is both salt affected and waterlogged (Kelly, 1995). Salinisation has been estimated to affect about 20% of the Upper Kent sub-catchment including salt-affected remnant vegetation and wetlands. This figure could rise to 30% unless planned management controls are effective (Kelly, loc.cit). Sub-surface soil acidity occurs in about 75% of the agricultural land in the moderate to high risk category, but wind erosion (with significant areas in the high risk category), sub-soil compaction, soil structure decline and water repellency are of lesser extent (Select Committee, 1990b). The Irwin Inlet into which the Kent River flows is classified as moderately enriched with 95% of the total load being from rural diffuse sources in the catchment (Select Committee 1990a)

Fig. 2 Upper Kent Catchment

Elevation Zones & Lakes



METHODS

Geomorphology and Geology

Geological information was collated from field observations, soil and rock cores and from existing geological maps and records. Preliminary field studies were conducted along accessible roads, routes and areas. These were followed by a stereoscopic study of coloured air photos (1:20 000) validated by more detailed field trips. Eleven traverses were selected in the catchment, mainly along existing roads to facilitate access. The traverse sections were selected to cover the different geological formations and the different landforms patterns existing in the catchment. Fifty-nine air-percussion holes and 22 wireline-cored holes were drilled in the eleven sections, and soil and rock samples were collected for laboratory analysis. Their location is shown in Figure 2. Holes were drilled using an air-percussion rig, with the drilling usually completed at hard rock. The cored holes were selected to cover the different hydrogeomorphic units (HGUs) and the different geological systems. Each section had one or two cored holes to give an adequate representation of the geological formations and the HGUs.

Groundwater Levels

Water levels were continuously recorded using conductance probes and water level recorders in 60 piezometers installed in the holes drilled in the geomorphology study. Barometric pressure was measured using temperature-compensated pressure transducers. Barometric efficiency was used to define types of aquifers in the catchment. Water-level fluctuations were analysed for seasonal and long-term trends. All holes were surveyed to a known datum and the water levels were reduced to Australian Height Datum (AHD). Water-level maps were prepared for the different subcatchments using newly developed hydrogeomorphic techniques (Salama et al., 1996a, 1997).

The constructed water-level maps were used in conjunction with the hydrogeomorphic classification (to be discussed below) to divide the catchment into areas of similar hydrogeological properties. This classification has also been used in other, complementary work to assign values for hydraulic conductivity based on rock type, lithological description and HGU. These hydraulic conductivity values are then used to construct flow nets and calculate fluxes in groundwater. The methodology used is described by Salama et al (1996b, 1996c).

Groundwater Quality

Electrical conductivity (mS cm^{-1}) and chloride concentration was measured in the laboratory for groundwater samples collected periodically from the 80 piezometers. Using a major ion analysis of virgin, uncontaminated groundwater samples collected from the installed piezometers, a regression was established between chloride concentration and total soluble salts (TSS). This relationship was used for calculating TSS for both groundwater and soil solution extracts from measured chloride concentration.

Table 1: Regressions used for calculating salt load from EM-39 downhole electrical conductivity readings

Hydrogeomorphic Unit (HGU)	Hole Number	TSS (kg m^{-3}) = a EC$_a$ (mS m^{-1}) + b			
		Unsaturated Zone		Saturated Zone	
		a	b	a	b
U1 - U2	K5, K4, KW3, KW5, Pine	0.0145	0.1219	0.011	0.4978
Lower U2	KW1, KW7, S3, S5, S6	0.017	-0.355	0.0072	1.7463
	N1	0.0182	-0.241	0.012	-0.072
	N2			0.012	-0.072
	SY2	0.0274	-0.335	0.0097	-0.6604
U1	KW8, M1, RG1, RG2, S7, SY1	0.01268	0.1087		
Low U2	M2, M3	0.015	-0.355	0.0097	0.6604
	MW5	0.015	-0.355	0.0184	-1.1603
	MW4			0.0184	-1.1603
	K3			0.0196	-0.254
	P3			0.009	0.248
	S1	0.019	-0.0155	0.0072	-1.7453
P1 - P3 and high L1 - L3	MW1, MW2, T2, T3, T5, T6	0.0173	-0.153	0.01463	-1.202
	T1	0.0153	-0.206	0.02495	-4.777
Low L1 - L3 and F1 - F3	SY4, SY5, SY6	0.01	0.7186	0.0072	1.7463
	P1	0.009	-0.335	0.0184	-1.1603
	RG3			0.0168	-0.7913
	RG4, RG5			0.0123	0.0715
Low U2 and F1 - F3	TU1	0.0097	0.129	0.0097	0.129
	TU2, TU3, TU4, TU5			0.0097	0.129
	P2			0.009	0.249
	SY3	0.0021	0.2457	0.0108	0.2309

Surface Water Sampling

The Upper Kent Catchment has been divided into 23 sub-catchments based on stream sampling points accessible from the road. Some of the subcatchments are nested. Surface water quality at 24 locations for streamflow and 6 lakes were sampled monthly between September 1992 and March 1993. Electrical conductivity and chloride ion concentration was measured for each sample. Major ions were measured on samples from 7 stream sites and 2 samples (September and January) for 3 lakes. These data were used to obtain relationships between electrical conductivity and chloride ion and sum of major ions (TSS).

Downhole Geophysical Measurements Of Electrical Conductivity And Resistivity.

Apparent electrical conductivity (EC_a) was measured at 0.10 m intervals in 81 piezometer tubes using a Geonics EM-39 downhole conductivity probe (McNeill, 1986). At selected sites of drilled or cored holes resistivity profiles were logged using surface time-domain electromagnetic methods (PROTEM 47; Knapton, 1994).

Salt Storage Distribution

The continuous cores from the 22 cored holes were sampled each 0.75 m and analysed for electrical conductivity (EC) and chloride concentrations in 1:5 soil-water extract. The measured concentration of total soluble salts (TSS) in the soil solution was correlated with the downhole electrical conductivity at the same position in the cored soil profile and a regression was developed for each hole to calculate the TSS for uncored holes at other locations. The results are shown in Table 1 for the relationship TSS = a EC_a + b. This correlation was improved by obtaining separate regression for the unsaturated and the saturated parts of the profile. Calculation of the average TSS content (kg m^{-3}) and the TSS storage (kg m^{-2}) were made. In areas where the correlation was poor between EM profile conductivity and the salt storage, regressions from similar HGUs having the same geology were used.

The salt content and salt storage results were compared with profile EM (Knapton, 1994), airborne EM conductance and magnetics (World Geoscience Corporation 1991).

Rainfall

Rainfall was measured at five sites. The first site was located some 8 km from the south coast where the Kent River crosses the south-west highway (N6131400 E503600). The second station is approximately 35 km from the coast, 1 km north of Roe Rd, on Nornalup north Rd (N6159600 E497100). The third station is 55 km from the coast on Turpin Rd. 2.5 km south of Muir Highway (N6184800 E528700). The fourth station is 89 km from the coast at Carabundup Homestead (N6184800 E528700). The fifth station is approximately 100 km north from the coast at San Mateo Station at Nuniup Rd. (N6193200 E544000).

Fig. 3 Upper Kent Catchment

Boreholes & Stream Sampling Points

LEGEND

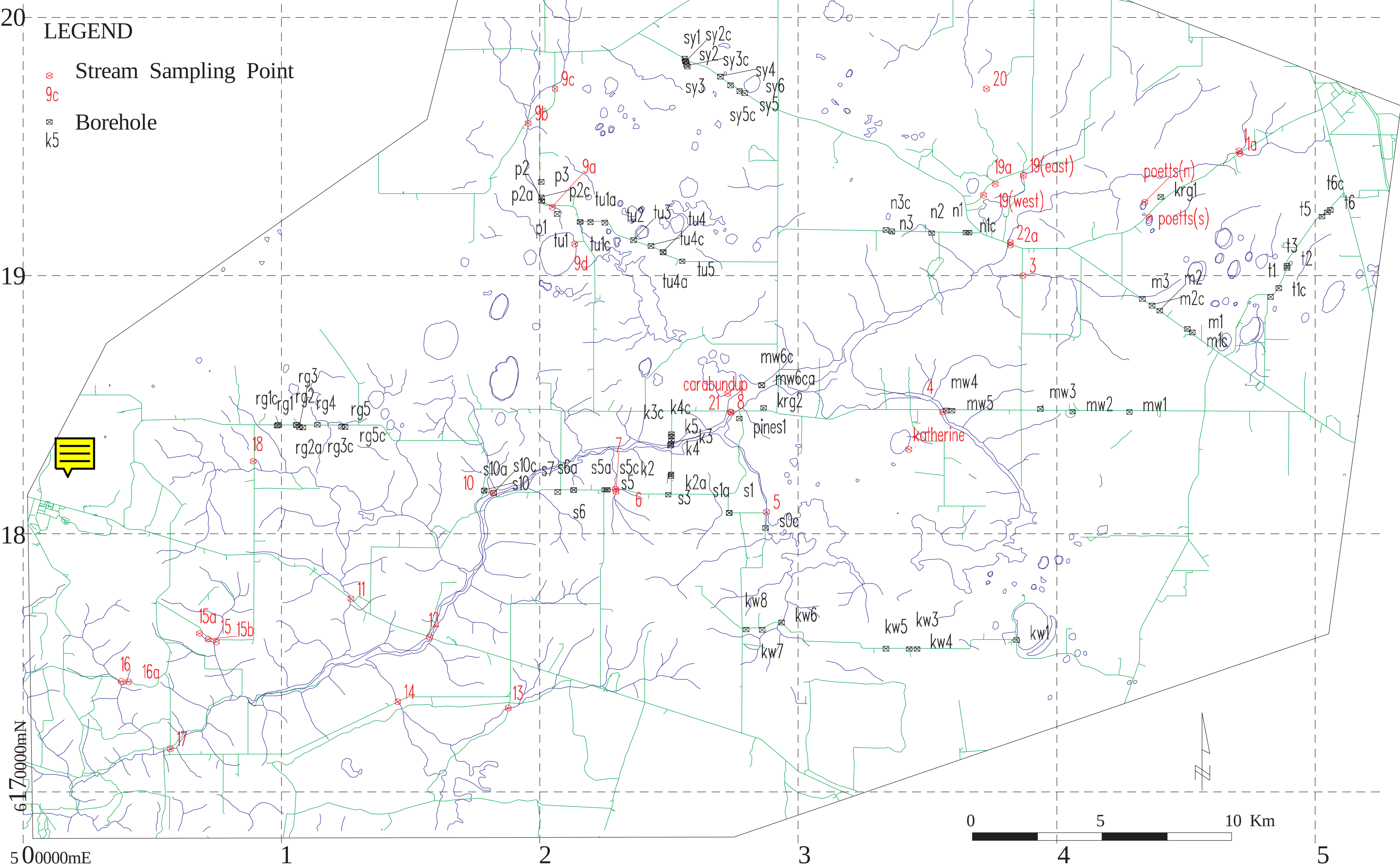


Figure 4: Three−dimensional view of the Upper Kent catchment showing the incised valley in the downstream end of the catchment and the low−lying country in the centre

Observer: 245
Angle: 1
Height: 1200000
Zcale: 50
Diagonal: 170

PHYSICAL CHARACTERISTICS OF THE UPPER KENT CATCHMENT

The land surface consists of a gently undulating (Figure. 2), upland plateau surface in the northeast. The elevation in the study area ranges from 185 to 280 m. The northern area of the catchment is characterised by flat swampy areas and lakes. From the edge of the upland plain, the plateau surface dips gently down to around 100 m elevation about 20 km inland from the coast. Land degradation problems include seasonal and permanent water logging, salinisation of land and water, soil acidity and, to a lesser extent, wind erosion. These are described fully by Kelly (1995)

Hydrology

The upper reaches of the Kent River (Figures. 3 and 4) follow an old meandering drainage system incised into a broad flat valley which commonly contains lakes, sand dunes and lateritic remnants (Churchward et al., 1988; Muhling and Brakel, 1985). The Kent River drains the northern upland plain and the western part of the plateau. Within the Upper Kent River catchment, the main river becomes more deeply incised in its lower reaches, while the tributary valleys remain broad, shallow and swampy (Figure. 4). The valleys are characterised by the presence of thick alluvial sediments.

Lakes are concentrated in a very systematic pattern of five main groups distributed according to three main trends. Each group is formed by a series of large- and small-diameter lakes, with the largest lakes occupying the northwest part of the catchment in a morass area.

The lakes occupy three main elevation ranges (Figure. 2): groups 1 and 3 in flat country having an elevation range from 215 to 230 m, group 2 in the plains occupying an elevation range between 245 and 260 m, and groups 4 and 5 in the morass country having an elevation range between 200 and 215 m. The lakes can also be seen to fall in two main axes: an east–west axis formed of groups 2, 3, 4 and 5 and a north–west axis formed by groups 1 and 4.

Geology

Most of the study area (Figure. 5) lies within quartzo-feldspathic gneiss of the Biranup Complex belonging to the Albany–Fraser Orogeny. Ten of the eleven traverses selected for the hydrogeomorphic study lie within this group. Only the Stockyard section lies within the granitoids of the Yilgarn Craton which stretches across the northern part of the Kent Catchment.

The Biranup Complex is a wide belt forming the northwestern part of the Albany–Fraser Orogen. It consist of quartzo-feldspathic gneisses, mainly derived from granitoid rocks interlayered with smaller amounts of metasedimentary rocks and metagabbro. The rocks are intensely deformed, showing a strong west-northwest trend in foliation. To the north, the complex is bounded by the Manjimup fault. To the south, the complex is bounded by the Northcliffe fault and the Nornalup complex (Myers, 1990). The Pemberton fault separates the two subsections of the Biranup complex. These major faults are associated with an east–west trending shear zone between the Yilgarn and the Albany–Fraser Orogen (Muhling and Brakel, 1985). Complementary sets of lineations trending northeast–northwest on the aeromagnetic map are prominent within this unit. These lineations are interpreted to be faults and shears, which can be directly attributed to the major east–west shearing processes.

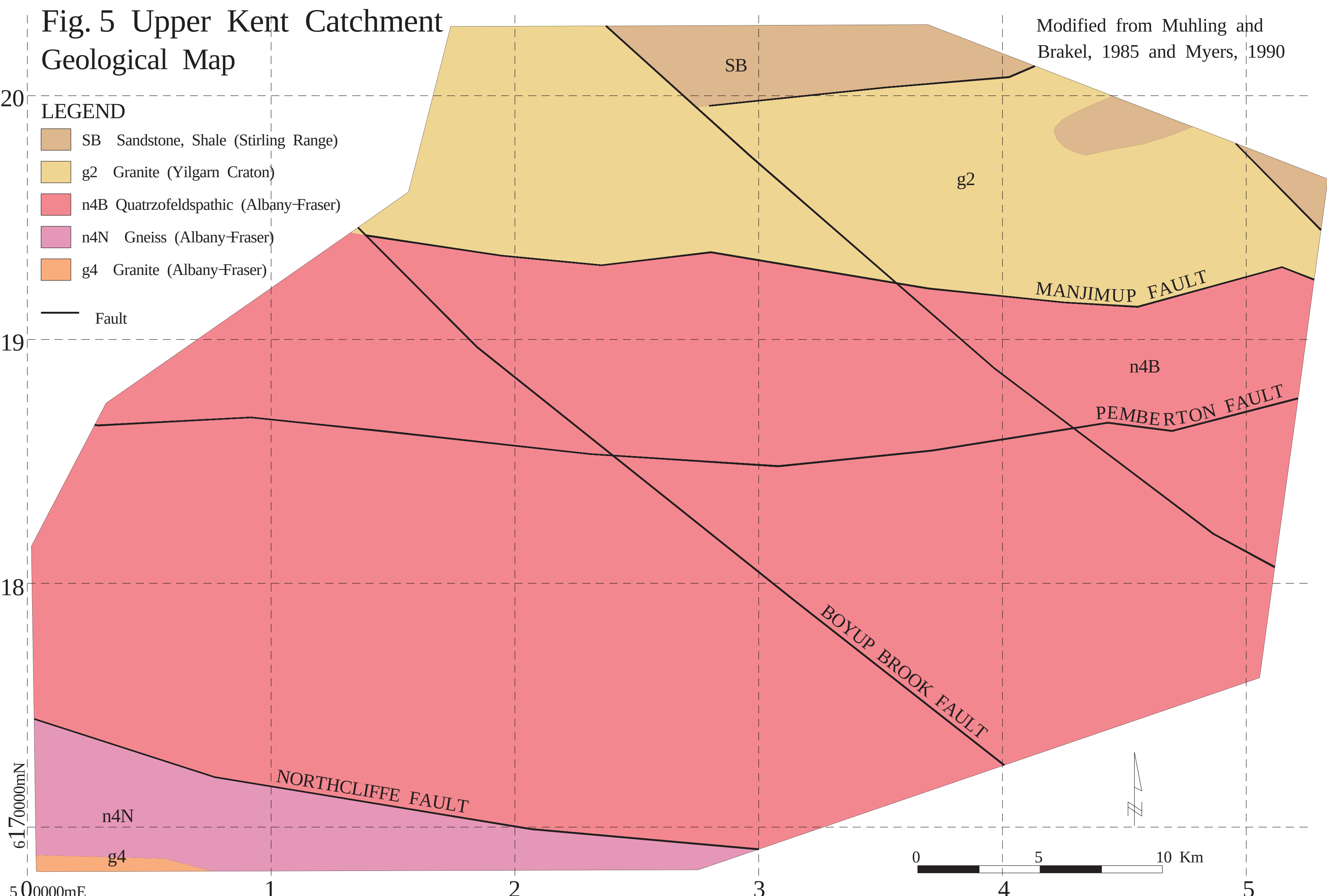
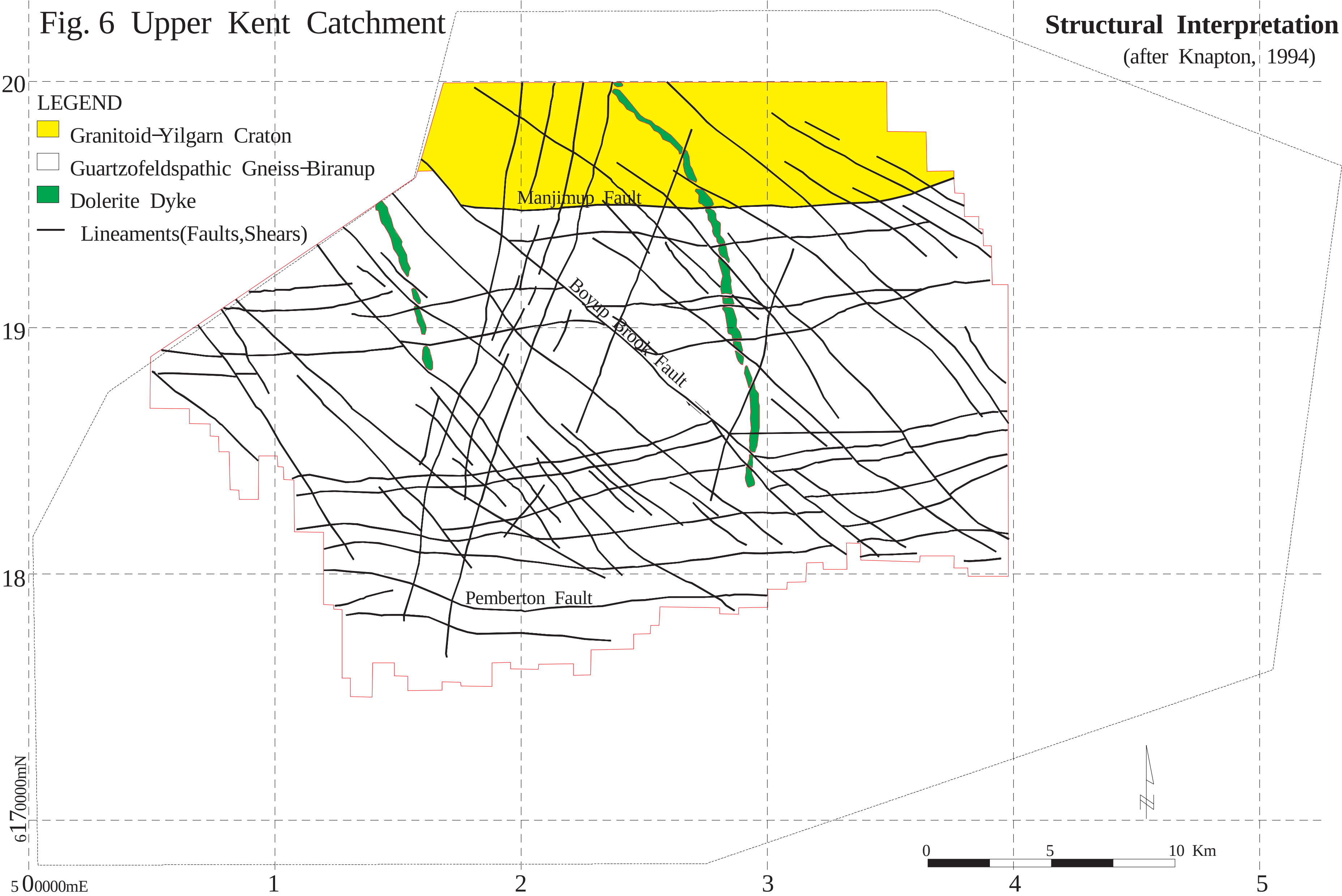


Fig. 5 Upper Kent Catchment Geological Map

Fig. 6 Upper Kent Catchment

Structural Interpretation

(after Knapton, 1994)



Structural Interpretation from World Geoscience Corporation Airborne Magnetics (after Knapton, 1994)

Description of the geology from the drilled holes in the 11 sections show the following features:

- In the undulating country, the high areas are usually lateritic, weathering increases downslope and the midslopes are characterised by the presence of relatively thick colluvial and sedimentary deposits. The thickness of the sediments increases downslope as well as downstream in the channels.
- The weathering profiles are characterised by the presence of three different layers: top leached layer, middle mottled layer and a lower layer having rudimentary bedrock fabric.
- The northern lakes areas are characterised by the presence of lignite, coal, spongelites and thick layers of clay and mud intercalated with well-rounded fine sands.
- The sediments in the streams are not well developed indicating short travel distance and low-velocity streams.
- The plains are characterised by the presence of a thin sedimentary sequence and, in most cases, colluvial cover underlain by highly weathered bedrock.

Structures

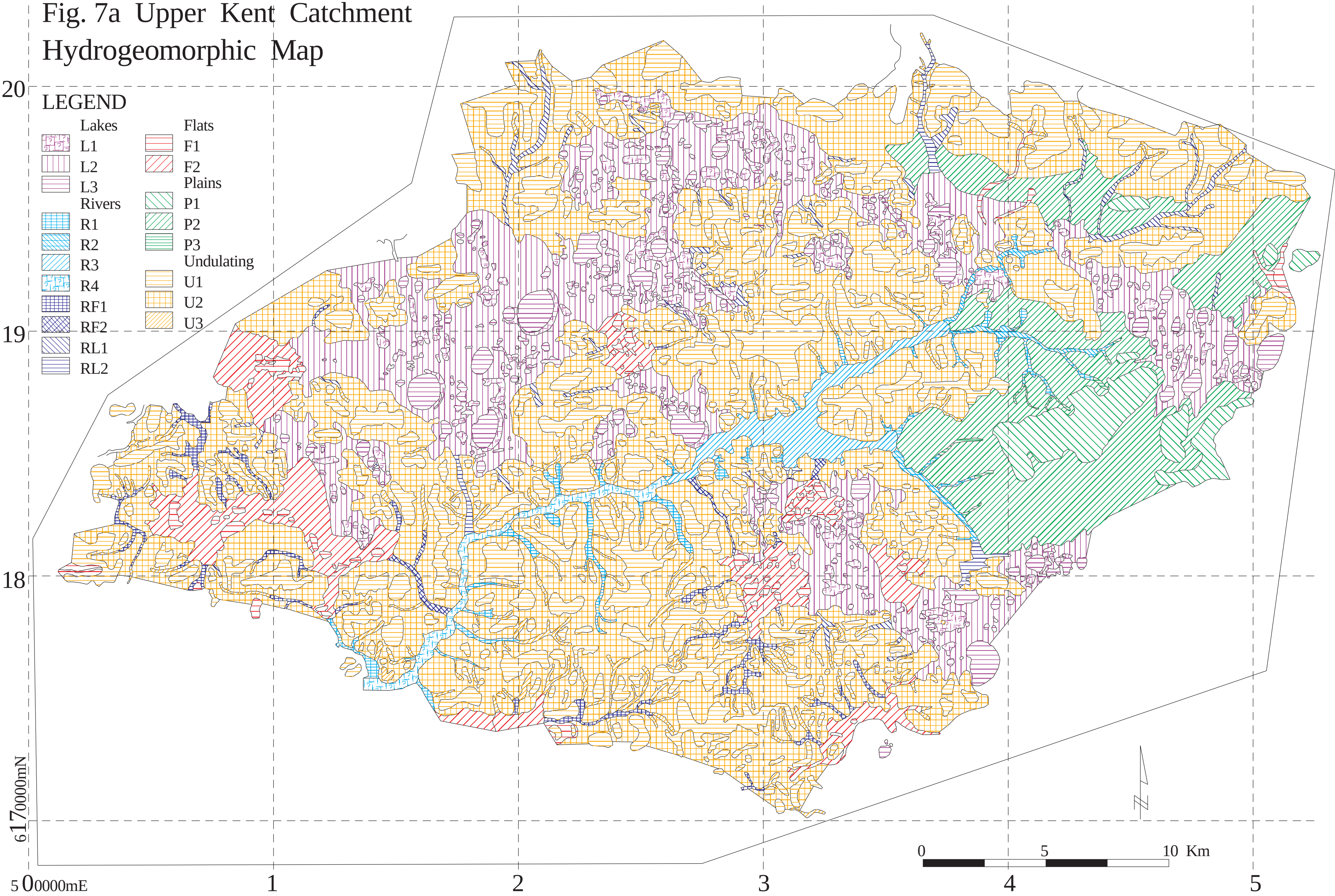
Bureau of Mineral Resources (BMR) Bougeur gravity and regional magnetic maps show a large linear feature extending in a west-northwest direction (Figure. 5). The gravity high in the north of the shear zone is due to the granitoids of the Yilgarn Craton, while the gravity low to the south of the lineament is due to the Burnside Batholith. The lateral extent of the shear zone is controlled by the Manjimup, Pemberton and Northcliffe faults to the north, centre and south of the shear zone, respectively.

The shear zone is associated with a set of faults trending northwest and northeast. The major lineament follows a southwesterly trend in the gneiss but seems to be reversed in the granitoid to a southeasterly trend (Muhling and Brakel, 1985).

Both areas have been equally affected by the major faulting and shearing which occurs at the junction of two major cratons. The contact between the two major units is defined by the east–west trending Manjimup fault. Three other major faults cross the catchment: the largest one is the central northeast–southwest Boyup Brook fault which extends for a long distance in the southwest of Western Australia. This fault defines the axes of most of the low-lying and lake country in the Upper Kent catchment. The second fault, the Pemberton fault, crosses the catchment from the east to the west, and the Kent River follows this fault for most of its westerly course in the catchment. The third fault is the southern east–west Northcliffe fault which defines the boundary between the elevated country in the south and the low-lying country in the north.

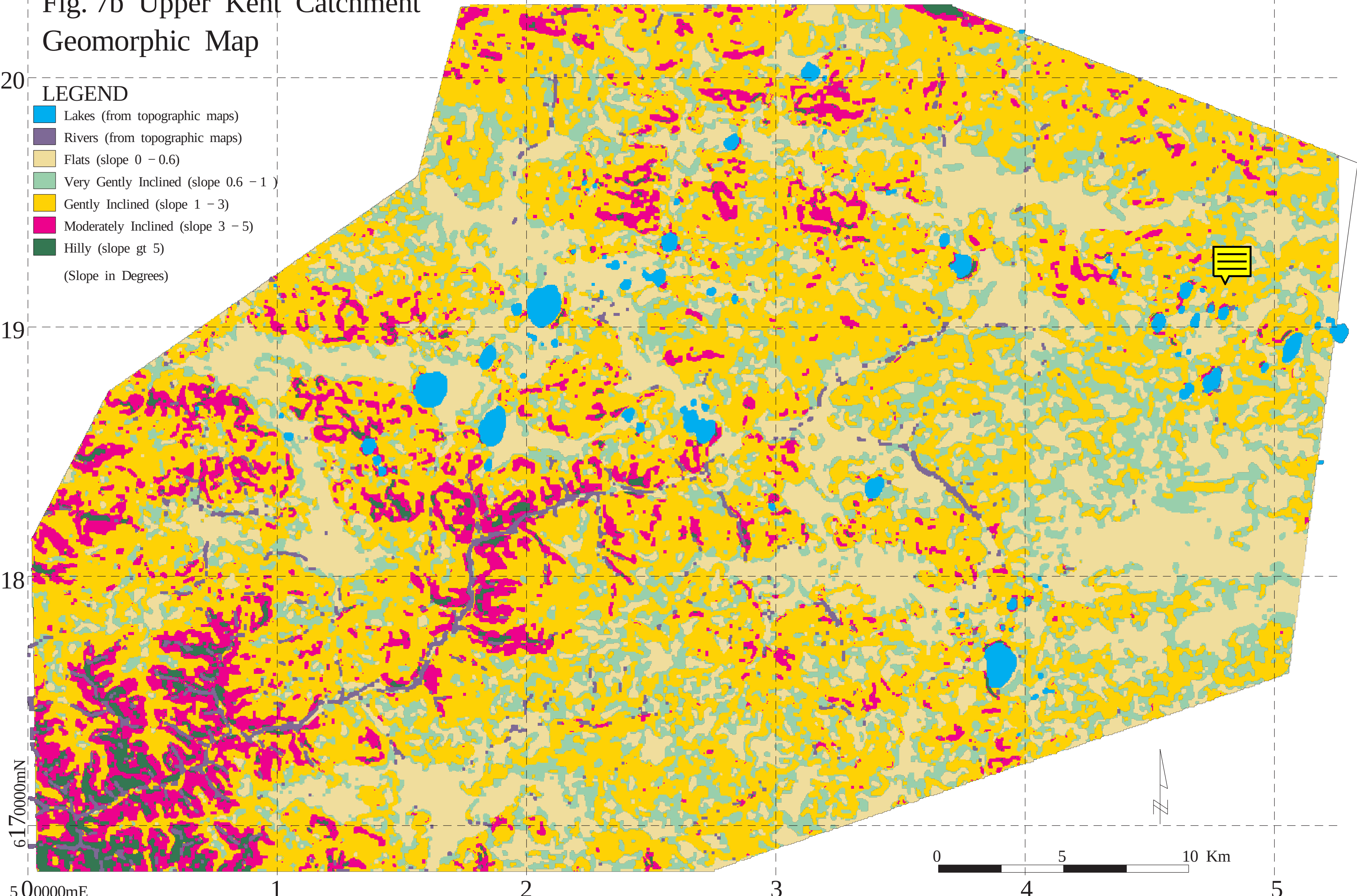
The interpretation of the World Geoscience Corporation (WGC) magnetic map (Figure. 6) shows that the catchment is comprised of three basic units, as indicated by their particular magnetic character (Knapton, 1994). The northern low-amplitude magnetic areas are associated with the granitoid of the Yilgarn Craton. These magnetics suggest little deformation except where the Yilgarn Craton comes into contact with the shear zone. The central zone shows much deformation and is bounded to the north by the Manjimup Fault and to the south by the Pemberton Fault. Fault areas are characterised by low magnetics. The correlation of the magnetics data with landform units shows that the fault zones are covered by marine sediments which are 100 m thick in some places. The high magnetic area to the south shows strong foliation and deformation in an east–west strike direction.

Fig. 7a Upper Kent Catchment Hydrogeomorphic Map



Interpreted from 1 : 20,000 Air Photos

Fig. 7b Upper Kent Catchment Geomorphic Map



Upper Kent Catchment Geomorphic Map

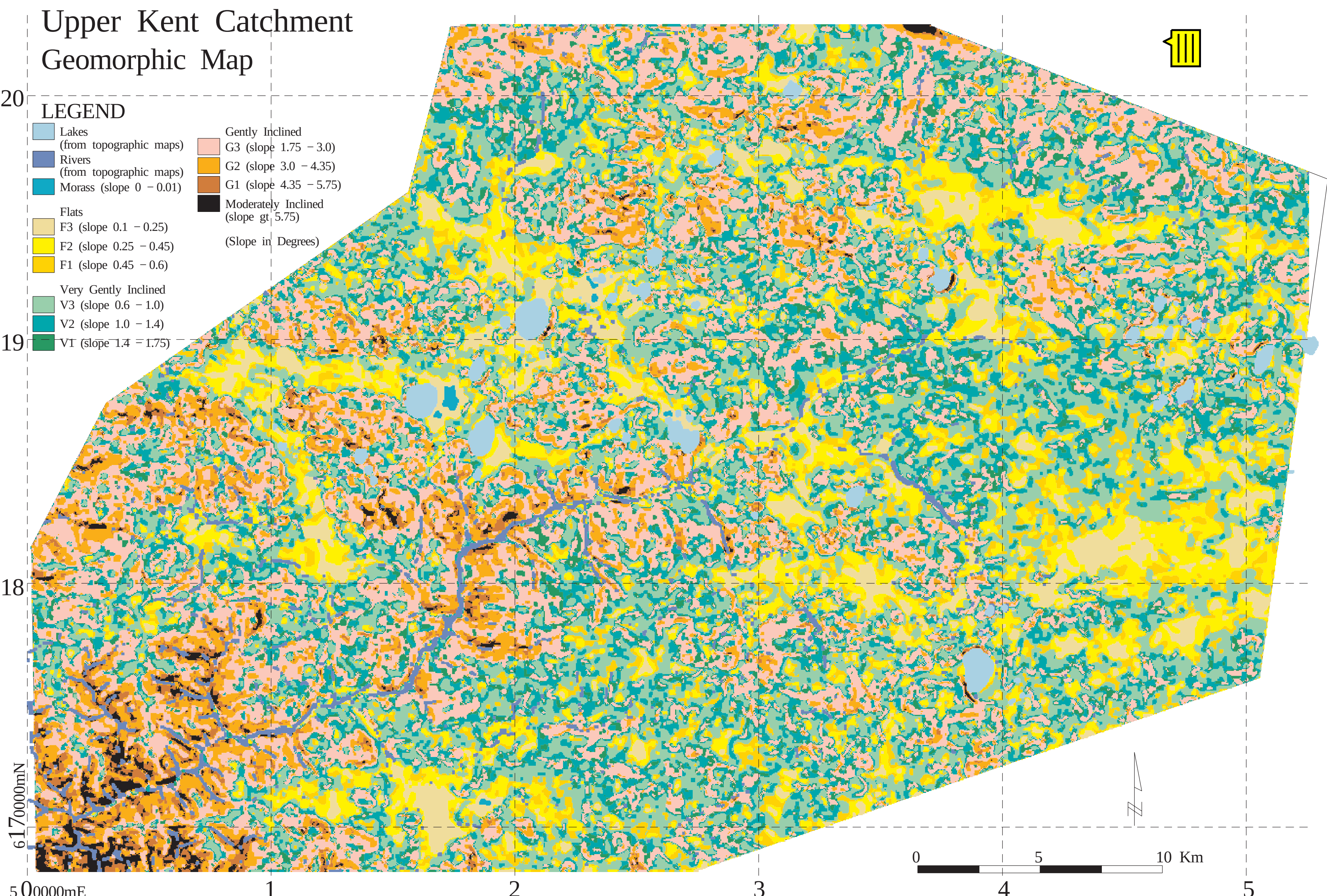


Table 2: The Hydrogeomorphic Units (HGU) - their geologic and geomorphic provinces and their hydrogeological significance.

HGU	Geologic and Geomorphic Province	Hydrogeological Significance
U1	Lateritic, granitic hills and crests, scree in the halos	Deep groundwater levels, recharge areas
U2	Colluvium and sedimentary midslopes	Intermediate depth to groundwater level, recharge–discharge areas
U3	Sedimentary, colluvium and alluvium deposits of minor valley heads	Shallow water tables, major discharge areas at break of slope
P1	Gently undulating plains, shallow overburden	Intermediate groundwater levels
P2	Dissected undulating, poorly defined drainage lines	Shallow groundwater levels, low gradients
P3	Flat depressions, minor broad valleys, head of drainage lines	Seepage areas at break of slope
F1	Low-level flat to gently undulating rises, underlain by marine sediments	Shallow groundwater tables
F2	Broad swamps and poorly drained flats. Alluvial and marine sediments clayey at top and sandy from 5-10 m	Shallow to near-surface groundwater levels
F3	Swampy broad flats, duplex soils with very heavy clays. Ferruginous pan underlain by alluvial and marine sediments.	Shallow to near-surface and surface groundwater levels
L1	Relatively high hills to small rises and lunettes	Relatively deep groundwater levels
L2	Broad swamp tracts and palaeolakes underlain by lake deposits and marine sediments in some	Shallow to near-surface water levels
L3	Lakes and swamps, palaeolakes, paleodrainage lines and associated sediments (morass)	Surface water - inundation
R1	First-order minor streams, incised floor and usually developing at the break of slope of U3, P3 and F3	Groundwater discharge frequently developing at the break of slope
R2	Second-order streams formed by the junction of two R1 units, usually developing at break of slope	Groundwater discharge at break of slope
R3	Forms the third-order Kent River, characterised by broad valley floors. Associated with P and F country	Shallow groundwater during dry season, subject to inundation
R4	Incised form of R3 as the Kent River enters the Gneiss geological region	Groundwater discharge at the break of slope
R5	Deeply incised form of R4	Groundwater discharge at the break of slope

Two dolerite dykes extending mainly north–south are highly deformed and transected by the faults, suggesting that the dykes predate the faults and were probably deformed by the processes which produced the fault system (Knapton, 1994).

Hydrogeomorphology

Following the principals of dynamic mapping versus static mapping and to demonstrate the usefulness of the GIS techniques in production of hydrogeomorphic maps (Salama et al., 1996b and 1997), three hydrogeomorphic maps are produced for the Upper Kent River catchment. The first map (Hydrogeomorphic Map 1 in Figure. 7a, Table 2) is produced using the traditional airphoto techniques. The second and third maps are based on slope, break of slope and curvature, the nomenclature of Speight (1980) was used for classifying the different units. In the second map (Hydrogeomorphic Map 2 in Figure. 7b, Table 3) the catchment has been classified into five broad unit. These units are: undulating areas (U), plains (P), flats (F), lakes (L) and streams (R). In the third map (Hydrogeomorphic Map 3 in Figure 7c, Table 3) some of the units have been expanded and divided into three further units based on break of slope criteria, with the exception of the stream unit which was divided into five further units. Although the slope was derived from 25 m grid based on a 5 m contour, the interpolation of slope below 1^{o} is beyond the original information by a factor of <1.5.

The prepared hydrogeomorphic maps show the presence of large areas of flats in the northern part of the catchment. Gently undulating plains cover the eastern part of the catchment, while in the south and southwestern parts, hills and undulating country are more predominant. The catchment is characterised by the presence of a large number of lakes. There are no perennial streams and the drainage density is very low.

Table 3: Relationship between the hydrogeomorphic units (HGU's) produced by the different hydrogeomorphic techniques

Hydrogeomorphic 1	Hydrogeomorphic 2		Hydrogeomorphic 3	
Hydrogeomorphic Unit	**Hydrogeomorphic Unit**	**Slope Range in degrees**	**Hydrogeomorphic Unit**	**Slope Range in degrees**
Lakes L1-L3	Lakes L1-L3		Lakes L1-L3	
Streams R1- R4, Rf1-Rf2, Rl1-Rl2	Streams R1-R4		Streams R1-R4	
			Morass L3	0.00 - 0.01
Flats F2	Flats F1-F3	0.00 - 0.60	Flats F3	0.01 - 0.25
F2			F2	0.25 - 0.45
F1			F1	0.45 - 0.60
Plains P3	Very gently Inclined P1-P3	0.60 - 1.00	Very gently Inclined V3	0.60 - 1.00
P2			V2	1.00 - 1.40
P1			V1	1.40 - 1.75
Undulating U3	Gently Inclined U2-U3	1.00 - 3.00	Gently Inclined G3	1.75 - 3.00
			G2	3.00 - 4.35
U2			G1	4.35 - 5.75
U1	Moderately Inclined	> 5.00	Moderately Inclined	> 5.75

Note: Slope is not quantified for Hydrogeomorphic 1 technique.

Table 4: Distribution of hydrogeomorphic units in the Upper Kent River Catchment

Hydrogeomorphic Unit		Slope Range in degrees	Unit Area km^2	Unit Area %	Basic Unit Area %
Streams	R1 - R4		75.9	5.2	5.2
Lakes	L1 - L3		19.6	1.3	1.4
Morass	L3	0.00 - 0.01		0.1	
Flats					25.2
	F3	0.01 - 0.25	98.5	6.8	
	F2	0.25 - 0.45	147.3	10.2	
	F1	0.45 - 0.60	119.2	8.2	
Very gently inclined (Plains)					39.6
	V3	0.60 - 1.00	265.6	18.3	
	V2	1.00 - 1.40	186.5	12.9	
	V1	1.40 - 1.75	121.3	8.4	
Gently inclined (Undulating)					27.8
	G3	1.75 - 3.00	259.5	17.9	
	G2	3.00 - 4.35	110.5	7.8	
	G1	4.35 - 5.75	32.9	2.3	
Moderately Inclined	U1	> 5.75	11.1	0.8	0.8
TOTAL			1448	100.0	100.0

Hydrogeomorphic Units (HGU)

A description is given here for the units of Hydrogeomorphic Map 1 (Table 2). This description applies similarly to Hydrogeomorphic Map 2 and Hydrogeomorphic Map 3 by comparing the similar units in Table 3. The proportion of each HGU in the expanded classification given in Map 3, and Table 3, for the Upper Kent Catchment is given in Table 4.

- Undulating (U1–U3)

This unit ranges from gently undulating surfaces made up of broad divides to short, gentle slopes in the north and east and hilly terrain in the southwest part of the mapped area. The U1 unit is generally formed of lateritic soils and is predominantly duricrust in feature. Soils vary from gravelly duplex soils in the highs (U1) to shallow duplex soils in the midslopes (U2), and to sandy duplex soils in the lower slopes (U3). The aquifers are unconfined to semi-confined in this unit.

- Plains (P1–P3)

This unit is a broad expanse of relatively flat country with little or no dissection. It is formed mainly of very gently undulating surfaces with undefined drainage lines, terminating in broad-type valleys with no apparent drainage pattern in the rises. The midslopes are characterised by dissected undulating plains with gently sloping surfaces and poorly defined drainage lines. The minor valleys at the lower slopes form the head of drainage lines.

- Flats (F1–F3)

This unit consists of swampy flats with broad drainage floors. Low-level rises are situated in broad flat swampy tracts that gradually drain into broad swampy, poorly drained, flats which are seasonally inundated. Soils vary from duplex with very heavy clays to deep fine sandy clays, occasional orange earths, and some sandy areas. Ferruginous pans at varying depth (0.3 to 1.5 m) and continuity outcrop in most of the flat area.

- Lakes (L1–L3)

The catchment is characterised by the presence of circular lakes varying in size from 0.1 to 3.0 km^2. The lakes extend along an east–west line north of the Kent River and are nearly parallel to it. Most of the lakes receive surface flow through well-defined valleys. The outflow from these lakes is not as well defined as the inflow and may be via the groundwater system. The lakes are more prominent in the northern area of the catchment, where the flats dominate.

The Lakes Unit is made up of a complex series of landforms, formed from an assembly of a reworked version of the U, P and F units described previously. It varies from being almost flat to quite elevated undulating country. A few lakes are characterised by the presence of hills. These may be relatively high hills as found near Lake Kwornicup, varying to small rises on flats and lunettes, found associated with Lake Poorrarecup. The hills grade into broad swampy tracts gently draining towards well-formed lakes in most cases or towards palaeolakes and paleodrainage lines.

- Streams (R1– R5)

Due to the flat nature of the Upper Kent catchment, streams are not well defined, especially in the eastern part of the catchment, and so the following classification was adapted. R1 streams are first-order minor streams, with a slightly incised floor and usually developing at the break of slope of U3, P3 and F3 units. R2 streams are second-order streams formed by the junction of two R1 streams and are also associated with either a break of slope or a gradational change in slope. R3 forms the third-order Kent River, and is characterised by broad valley floors in the plains and flat country. R4 streams have a relatively well-developed channel which forms when the Kent River enters the undulating country. A R5 stream is a deeply incised form of a R4 stream where the river enters the uplifted high country.

Table 5 The groundwater characteristics of the hydrogeomorphic units

HGU by Technique 1	HGU by GIS Technique	EC mS/cm	Average depth to bedrock m	Depth to ground-water m	Water level rise m	Water level fall m	Water level rise in 1994 m
Lakes lower L3	4	21.7	13	2.9	0.6	1.1	0.7
Flats F1-F3	5	14.0	11	2.6	0.5	0.5	0.3
Plains P1-P3	6	10.1	14	2.6	0.3	0.3	0.2
Lakes upper L1-L2	7	22.1	18	2.0	0.6	0.8	0.4
Undulating U3	12	18.8	18	6.1	0.4	0.5	0.4
Und. Lower U2	13	18.7	16	3.2	0.5	0.9	0.5
Und. Upper U2	14	16.0	16	5.6	0.1	0.1	0.1
Und. Lower U1	15	13.7	15	5.7	0.5	1.0	0.7
Und. Upper U1	16	12.4	22	7.6	0.7	1.0	0.7

Groundwater

The drilling technique used (RAB) allowed maximum depth penetration of both the unconsolidated material and the highly weathered bedrock. Therefore, the final depth of the hole is assumed to indicate a base which can be either bedrock or a hard pan.

Hole depths ranged from 5 to 30 m (Table 5). The deep holes were drilled in the lakes system, where thick sedimentary deposits were encountered. Due to the caving nature of the lake deposits it was difficult to reach a hard base and in most cases it was beyond the capacity of the rig. The average depth of holes drilled along the sections shows that the deepest holes are in the undulating country (U1), followed by all lakes and plains units, then the other units of the undulating country (U2 and U3).

Although relatively deep (>20 m), no water-bearing formations were encountered in the holes drilled in the upper parts of the catchment, where remnant vegetation has been retained (holes M1, S7, KW8 and SY1). Bore SY1 was completely dry at the completion of drilling, but accumulated a few centimetres of water during the rainy season which dried out during the summer. Shallow bores in the lower areas of the landscape would normally encounter water-bearing formations at more than one depth.

It has been found that groundwater levels are usually 2–3 m below the surface in the lower parts of the landscape and above ground surface in discharge areas, especially at the break of slope between U3 and R1 units. Water levels increased in depth with increase in elevation. Water levels in the U1 units were usually >5 m deep. In uncleared areas water levels could be 24 m below the surface and the piezometers were completely dry in some native forest areas at the tops of the hills.

Analysis of the barometric efficiency (BE) of the monitored piezometers shows a wide range of variations in the BE, which is expected in boreholes drilled in different types of formations and completed at different depths. (The BE indicates the degree of confinement of the aquifer, the more confined the aquifer is the higher will be its efficiency) In general, the BE seems to be high in the midslope areas of the landscape and decreases at the areas of groundwater discharge. The lowest BE was recorded in the lakes area, although the holes seemed to penetrate thick clay and mud layer. Thick clay or mud layers would usually cause some confinement to the aquifers and a subsequent rise in the BE. This low BE indicates an unconfined aquifer, showing that the lakes are mainly groundwater discharge areas and that the aquifers are hydraulically connected.

The analysis of the water-level maps shows that groundwater levels replicate the surface contours. It also shows that groundwater gradients are steeper in the undulating country, steep near streams and groundwater discharge points, and flat in the lakes area.

Analysis of the BE, water-level patterns, drilling records and the lithological description of borehole logs shows that there are three main types of aquifers in the catchment:

1. an unconfined aquifer system which occurs mainly in the flats and lakes areas of the catchment. The aquifer material is mainly of sedimentary origin.
2. a semiconfined aquifer which is mainly of colluvial and partly transported material and is usually located in the midslopes and gently undulating parts of the landscape.
3. an aquifer which is overlain by clayey material and is semi-confined to confined.

From the hydraulic connectivity established by the BE study, it can be concluded that there is no one continuous aquifer system which extends or covers a large area. The aquifers are mainly disjointed and are controlled by the HGU characteristics (slope, break of slope and curvature). This does not exclude the fact that there is a continuos saturated zone which extends over most of the catchment.

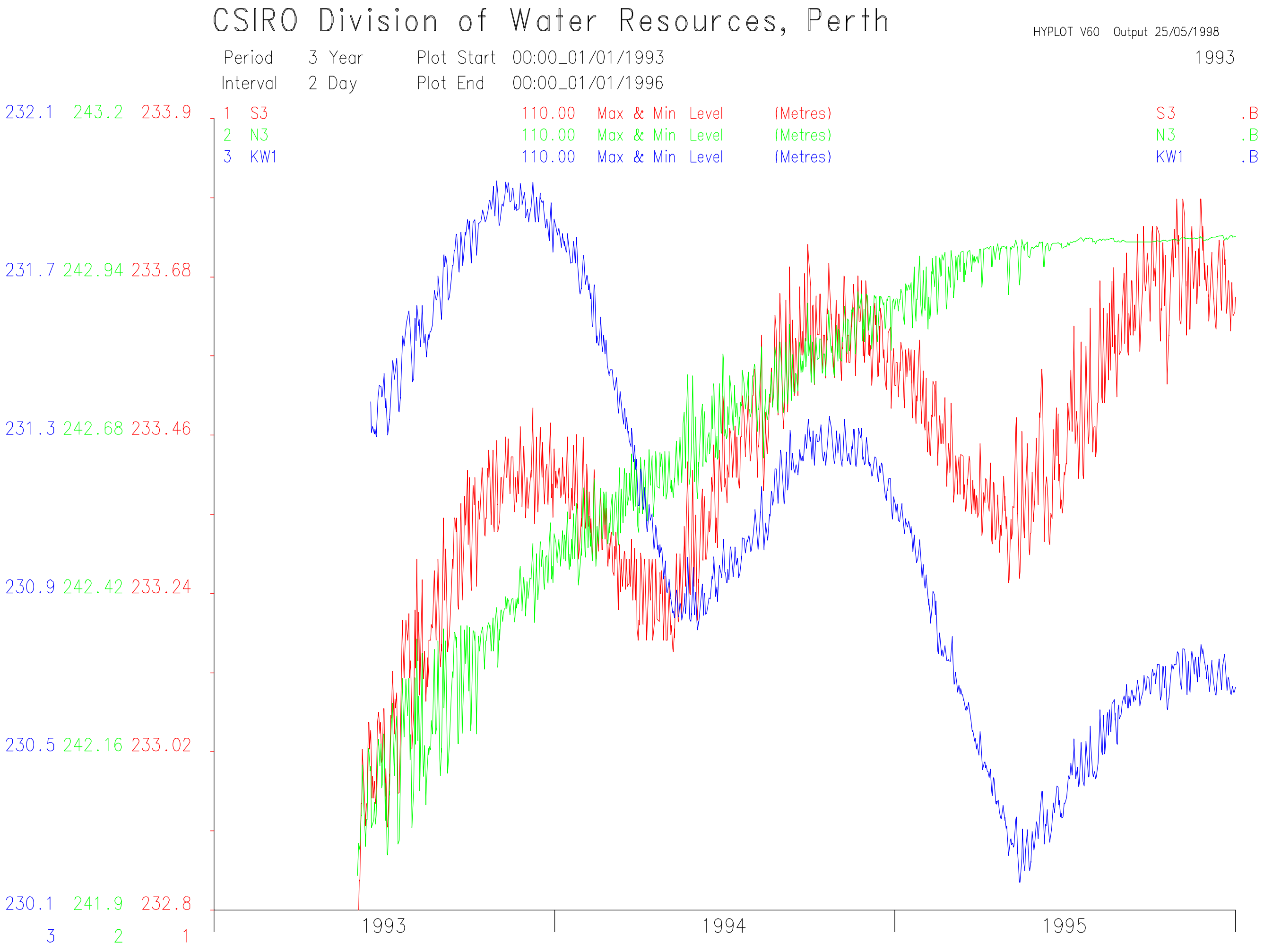


Figure 8: Water-level trends in the Upper Kent catchment, showing monotonically rising water levels in well N3, continuously rising water levels in well S3 and falling water levels in well KW1.

Water-level trends

Long-term periodic data for the Upper Kent catchment are available for some 64 piezometers installed by the Department of Agriculture and local Landcare Groups between 1984 and 1988. The majority are located in lower parts of the landscape where the water levels are less than 2 m deep, indicating groundwater discharge areas. The long-term trend of the water levels shows a general rise of 0.10 m y^{-1} for wells with water levels >2 m, while wells with water levels more than 5 m from the surface show an overall rising trend of 0.17 m y^{-1} (McFarlane et al., 1994 unpublished report).

The piezometers installed by CSIRO since 1993 are used in this study to interpret water-level trends in the different HGUs (Figure. 8). The analysis covers data from two years of continuously monitored water levels and compares the current trends with the previous results from the catchment (McFarlane et al., 1994 unpublished report) and similar trends from studies in other catchments (Salama et al., 1991, 1993b; Salama and Bartle, 1995).

The net seasonal rise in water levels ranges from 0.1 m in the lower parts of the landscape to 1.7 m in the mid- and high-slope areas, while the net fall in water levels ranges from 0.2 to 2.4 m in the upper reaches of the catchment.

The analysis of the water levels in the different HGUs shows the following trends: upperslopes (U1, U2 upper): continuously rising water levels (N3, MW2), midslopes (U2 lower and U3): seasonally fluctuating water levels but with a rising trend (S1, MW1) and in the flats and lower parts of the landscape seasonally fluctuating levels.

Although the seasonal trend is variable and dependent not only upon rainfall intensity, duration and seasonal distribution, but also on the hydrogeological characteristics of the HGUs. The overall long-term trend from previous studies (McFarlane et al., 1994 unpublished report) indicates that water levels are rising in the uncleared parts of the uplands and midslopes at rates ranging from 0.05 to 0.2 m per year.

Water Chemistry - Surface Water

Surface water quality in the streams varies considerably depending upon rainfall and runoff at the time of sampling and on the time of the year. The electrical conductivity (EC) of the water varies from 0.5 mS cm^{-1} in first order (R1) streams to 10.0 mS cm^{-1} near saline lake discharge areas. The water quality in the lakes ranges from 10.5 mS cm^{-1} (for Lake Nunijup) to 46.5 mS cm^{-1} (for Lake Katherine).

Historical records show that salinity in the lakes is continuously rising. For example, salinity in Lake Poorrarecup was measured as 6920 mg L^{-1} (average of 6 samples, September to March) with an increasing trend throughout that period (4350 to 8820 mg L^{-1}) as might be anticipated from the seasonal factors of run-in and high summer evaporation potential. This is an increase from the near constant value of about 5000 mg L^{-1} in the 1978-1979 study of Collins and Fowlie (1981) and shows a historic trend at a rate of 230 mg L^{-1} per year since about 1964 (Bestow, 1979). Bestow postulated that the increase in salinity was caused by groundwater discharge into the lake depositing salt at a rate of 400 tonnes/year. The salinities of Lake Nunijup, average of 5700 mg L^{-1}, and Lake Katherine, average of 23450 mg L^{-1}, were reasonably constant over the sample period, though with expected higher salinities in the summer months.

From the stream sampling it can be shown that the sub-catchments in the upper south-east part of the catchment (Table 6) discharge high salinity water (average 10880 mg L^{-1}) into the Kent River near Nunijup South Road. This is in contrast to the sub-catchments along the rest of the southern boundary of the Upper Kent River catchment where peak salinities of streamflow are less than 3000 mg L^{-1}. The sub-catchments on the northern and western side of the Upper Kent River catchment fall into an intermediate category with peak salinities in the range 3000 to 11000 mg L^{-1}. A more detailed analysis of the available data is given in Williamson and Ferdowsian (1997).

Water Chemistry - Groundwater

Groundwater quality data are given in Table 5 as average EC for samples from piezometers in each HGU. Measured values for aquifers vary from 2.4 mS cm^{-1} in the undulating country (P3) to 30.0 mS cm^{-1} in the lakes (L3) areas. In the plains area groundwater salinity is higher than 30.0 mS cm^{-1} (T6). Average groundwater salinities of the different HGUs show that groundwater salinity is very high in the lakes area (≈22 mS cm^{-1}), decreasing in the undulating country, with the lowest salinity in the high undulating country of unit U1 (12.4 mS cm^{-1}).

Table 6: Measured salinity (as mg L^{-1} TSS) of streams and lakes in the Upper Kent River Catchment for 1992/93. (based on relationship of sum of major ions with EC)

STREAMS

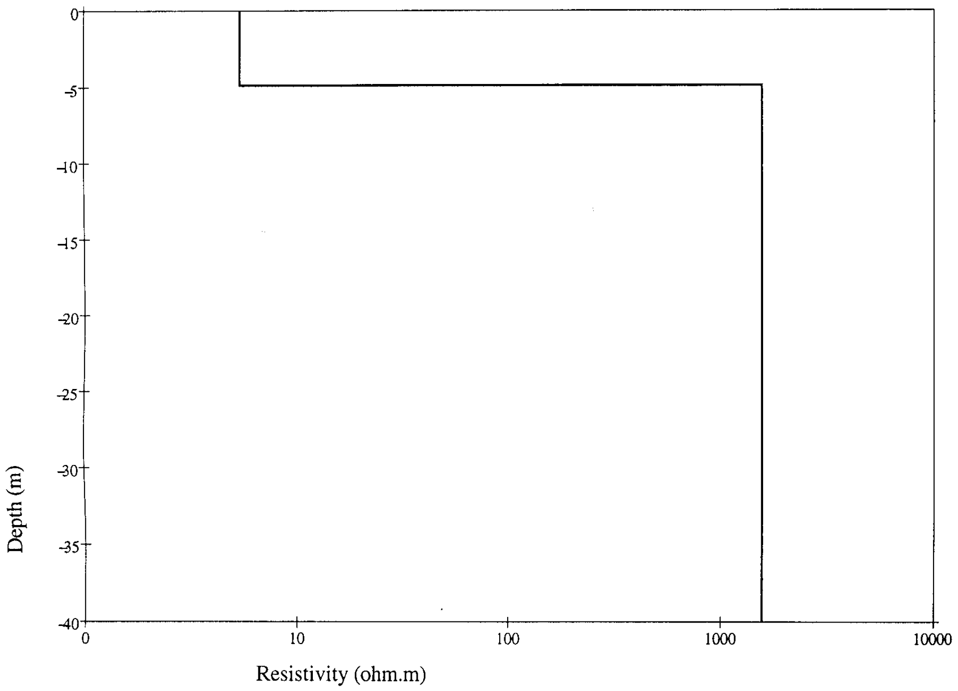
Sample Location	14 September	2 October	6 November	13 December
1	867	2192	ns	1325
1A	1023	1271	ns	1374
2	1277	3123	5836	8033
2A	1287	3397	5603	10803
3	1504	8761	14270	18995
4	1412	3938	10615	10677
5	943	1185	2324	3117
6	723	5894	9682	11243
7	792	5778	9620	13746
8	1228	1320	2039	2639
9A	862	2867	5545	5661
9B	1007	5603	ns	20888
9C	1282	5661	12453	15194
10	1613	4365	10552	11623
11	782	3369	7852	3967
12	1526	4080	9067	7792
13	489	1645	2617	1423
14	373	1309	4285	1488
15	824	1875	3600	3324
15A	1667	2501	3196	3735
15B	1700	2534	3280	3780
16	916	2055	3330	3684
16A	1558	3017	4336	5603
17	1629	3831	7253	6364
18	329	1212	2900	3106
19E	814	4920	ns	ns
19A	546	1733	3848	4593
19W	1217	3532	5475	5836
21	2050	4308	13942	10490

Note: ns no sample taken usually due to cessation of streamflow

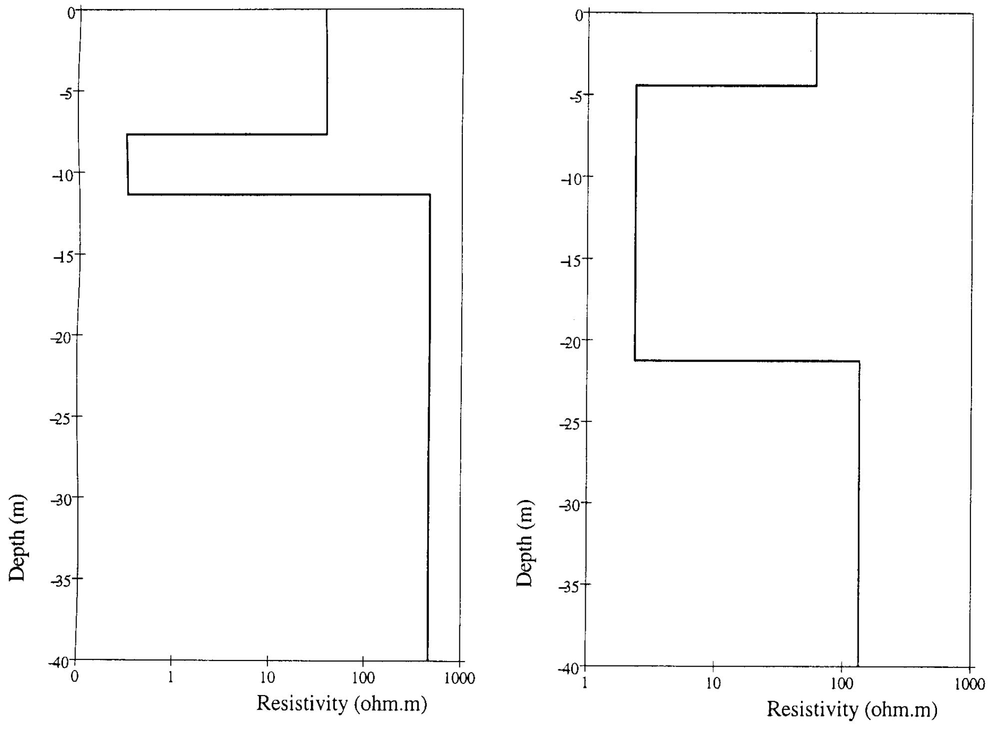
LAKES

Lake Name	4 Sept 1992	2 Oct 1992	6 Nov. 1992	13 Dec. 1992	22 Jan 1993	4 March 1993
Nunijup	5836	5226	5371	5504	5953	6340
Poorrarecup	4353	6481	6896	7074	7912	8822
Katherine	926	23472	24128	25159	30312	36690
Carrabundup	ns	ns	9806	10178	ns	12645

Note: ns no sample taken



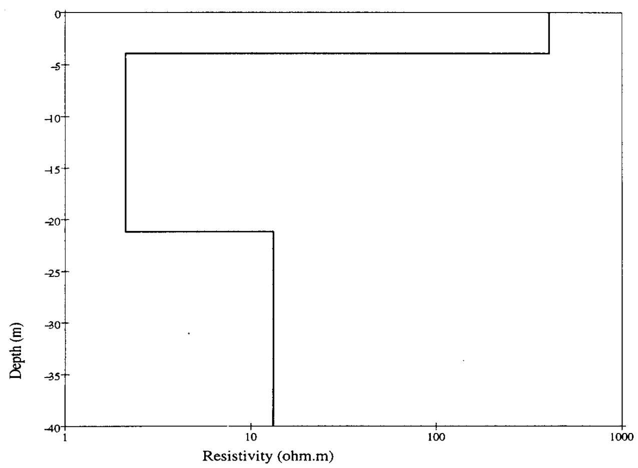
Curve Type A

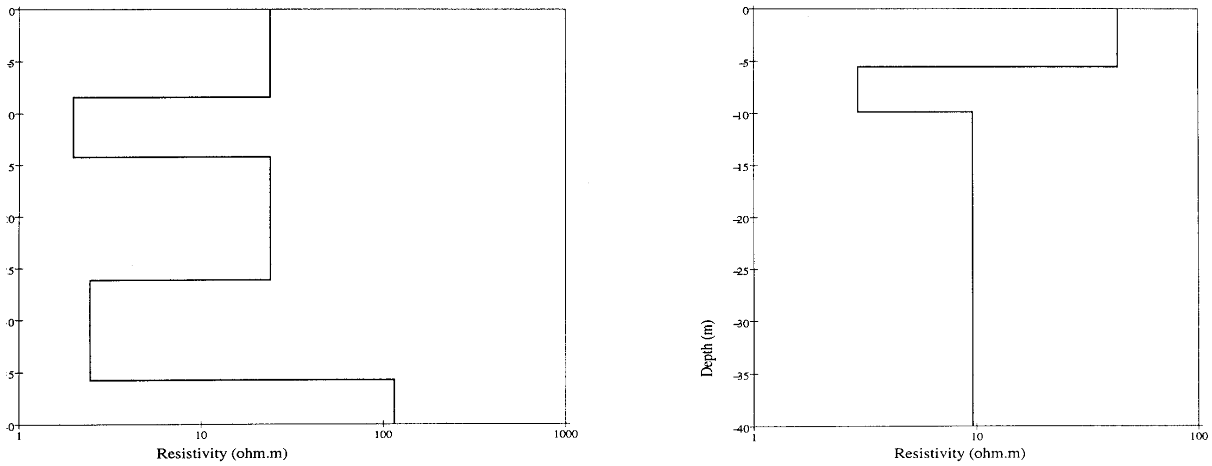


Curve Sub-type B1

Curve Sub-type B2

Figure 9a: Geophysical resistivity profile types A, B1 and B2 for regolith in Upper Kent Catchment (modified from Knapton, 1994)


Curve Type C


Curve Type D

Curve Type E

Figure 9b: Geophysical resistivity profile types C, D and E for regolith in Upper Kent Catchment (modified from Knapton, 1994)

SALT DISTRIBUTION IN THE LANDSCAPE

The results from the various geophysical methods - layered model (Protem-47), down-hole profile (EM-39), airborne electromagnetic (Questem) - together with profile salt content calculated from the core samples and the groundwater salinity, were used to determine the distribution of salt in the landscape. The electrical resistivity measured in field soil profiles have been found to correlate well with the salt content profiles (Salama et al 1994a; Buselli and Williamson, 1996).

Layered Resistivity Model - PROTEM-47

The apparent resistivity obtained from the inversion of the PROTEM-47 resistivity measurements shows five representative profile types (Knapton, 1994) are given in Figure. 9. Salt content is inversely correlated to resistivity, that is, high resistivity indicates low salt content. Four of the 5 types have high resistive values near the soil surface.

- Type A shows resistivity increasing at all depths.
- Types B1 and B2 have high resistivity near the surface, changing to low resistivity at middle depths and returning to high resistivity at greater depth. Type B1 and B2 vary in the thickness of the low resistivity middle zone - thick (≈ 10-15 m) for Type B1 and quite thin (≈ 5 m) for Type B2.
- Type C is similar to Types B1 and B2 also showing high resistivity near the surface, changing to low resistivity at middle depths and returning to high resistivity at greater depth. But for Type C the resistivity at depth is significantly less than near the surface and can be seen as the reverse to Type A by having generally decreasing resistivity with increasing depth.
- Type D shows zones of variable resistivity within the profile with the highest resistivity at greatest depth.
- Type E is similar to Type C. This type shows a decreasing resistivity with increasing depth but with a thin zone of low resistivity in the 5 to 10 m depth interval.

Table 7: Relationship between Hydrogeomorphic Units, topography and groundwater slope, geophysical range and salt storage

HGU Technique 1	Slope of Soil Surface	Slope in Hydraulic Head	Min. EC mS m^{-1}	Max EC mS m^{-1}	Min. R ohm m	Max. R ohm m	Salt Storage kg m^{-2}
Lakes lower L3	0.0	0.0	56.1	372.6	0.8	1045.8	2.8
Flats F1-F3	0.1	0.1	85.8	330.4	1.2	337.5	2.9
Plains P1-P3	0.3	0.3	80.9	322.2	0.9	90.1	3.0
Lakes upper L1-L2	0.5	0.5	85.6	461.3	0.8	145.0	3.5
Undulating U3	0.8	0.7	64.7	368.2	4.2	266.3	3.0
Und. lower U2	1.1	1.0	30.7	359.9	1.6	185.1	2.7
Und. upper U2	1.6	1.4	34.3	265.8	1.6	60.5	2.4
Und. lower U1	2.1	1.9	30.1	298.3	1.9	277.1	2.3
Und. upper U1	3.4	3.0	17.4	307.4	2.3	144.8	2.1

Notes: Slope is in degrees. EC is electrical conductivity. R is electrical resistivity

Table 8: Geophysical and hydrological classification of borehole sites

Borehole Number	HGU Classification	Conductance (Questem) S m	Profile Type	Hydrological regime
K3	U2-Lower	4 -7	B1	Mid-slope
K4	U2-Upper	<4	D	Discharge
K5	U1	<4	B1	Mid-slope
MW1	P1	①	B2	Discharge
MW2	P1	①	E	Palaeo-channel
MW4	P2	<4	B2	Discharge
MW5	P2	4 - 7	B2	Discharge
MW6	R2	4 - 7	B1	Midslope
N1	U2-Lower	4 - 7	B2	Midslope
N2	U2	4 - 7	B1	Midslope
P2	L2	4 - 7	B2	Discharge
P3	U2-Lower	<4	B1	Midslope
RG1	U1	<4	E	Palaeo-channel
RG2	U2	<4	C	Discharge
RG3	F2	<4	C	Discharge
RG4	F2	4 - 7	B1	Midslope
RG5	L2	<4	C	Discharge
SC0	F2	4 - 7	C	Discharge
SC1	U2-Lower	4 - 7	D	Discharge
SC3	U3	<4	B2	Discharge
SC5	U2	<4	B1	Midslope
SC6	U2	4 - 7	E	Palaeo-channel
SC7	U1	<4	B2	Midslope
SC10	R4	<4	B2	Midslope
SY1	U1	<4	A	Recharge
SY2	U2	4 - 7	B1	Midslope
SY3	U2-Lower	>7	D	Discharge
SY4	L2	4 - 7	B2	Discharge
SY5	L2	>7	B1	Midslope
SY6	L2	4 - 7	D	Discharge
TU1	L2	>7	C	Discharge
TU2	L2	>7	C	Discharge
TU3	L2	>7	C	Discharge
TU4	L2	4 - 7	B1	Midslope
TU5	U2	4 - 7	E	Palaeo-channel

Note: ① these boreholes beyond the area covered by available QUESTEM data

Buselli and Williamson (1996) have described similar profile types based on studies in small experimental catchments in the Collie River Catchment. They recognised geomorphological relationships for the characteristics of each zone in the profile types. In the Kent Catchment the Types B1 and B2 follow the general description of Johnston and McArthur (1981), and Johnston (1987), and are referred to as bulge profiles. The profile type does give some indication of recharge conditions. Type A is a leached profile suggesting higher recharge than types C and E where overall decreasing resistivity with depth may indicate profile of low or no recharge. These types could be expected to occur in locations with discharging groundwater. Types B1 and B2, the classic bulge profiles, have been associated in other studies (eg Peck et al, 1981) with preferred channels which allow recharge to bypass zones of salt accumulation within 15 m of the soil surface. Type D is a complex recharge-discharge profile type possibly influenced by groundwater inflow from other zones.

The profile types are found also to correspond to the hydrogeomorphic unit classification of the catchment. Type A occurs in high topographical areas with high slope gradient corresponding to unit U1. Types B1 and B2 occur in mid-slope and gently undulating areas corresponding to units U2, U3, R1, R2 and P1. Type C correspond with areas on the margins of flats and lakes, while Types D and E are confined to the low parts of the landscape (flats and lakes) corresponding to units L1, L2, L3, F1, F2 and R3.

In general, the comparison of the results of the resistivity profile type curves with the HGU's showed very good agreement though a few anomalies do occur which are caused by local conditions (Tables 7 & 8). The recharge areas corresponding to hydrogeomorphic unit U1 were always associated with type A curve and the discharge areas corresponding to hydrogeomorphic units L1, F1 and F2 with type C and D curves.

Conductivity profiles - EM-39 downhole probe data

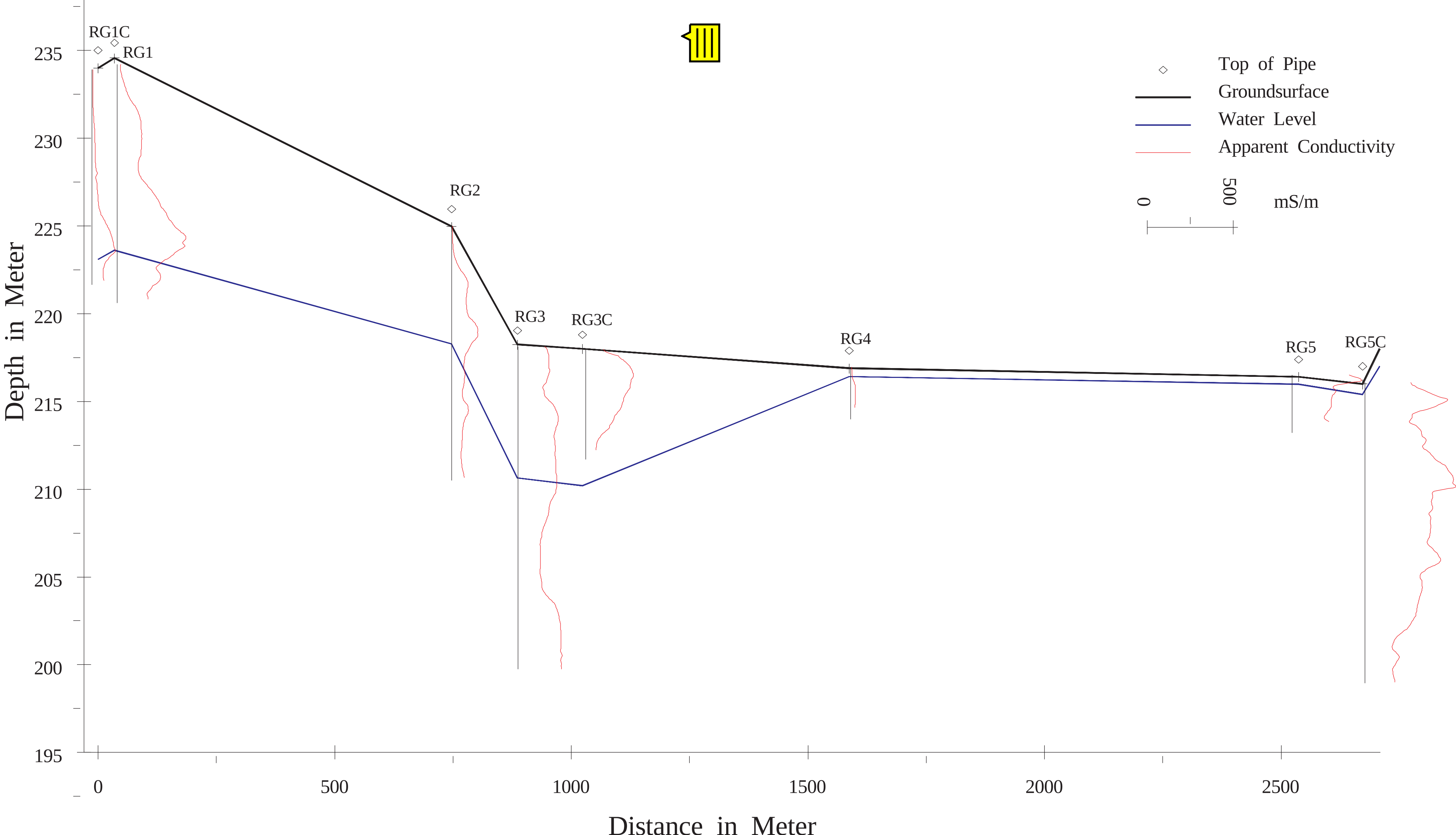
Electrical conductivity profiles using the downhole EM-39 probe were obtained giving more vertical resolution than the layered model of the PROTEM-47 where boreholes have been drilled and piezometer tubes installed. The conductivity profiles show a similar profile pattern to the results of a previous study in the wheatbelt in Wallatin Creek catchment (Salama et al., 1994a). One significant difference found was that the apparent conductivity is relatively lower (resistivity higher) in all types of profiles in the Upper Kent. Using the installed piezometers, EM-39 logs were obtained along each of the 11 geomorphological traverses. Results are shown in Figure. 10.

The 5 types of profiles identified are set out below.

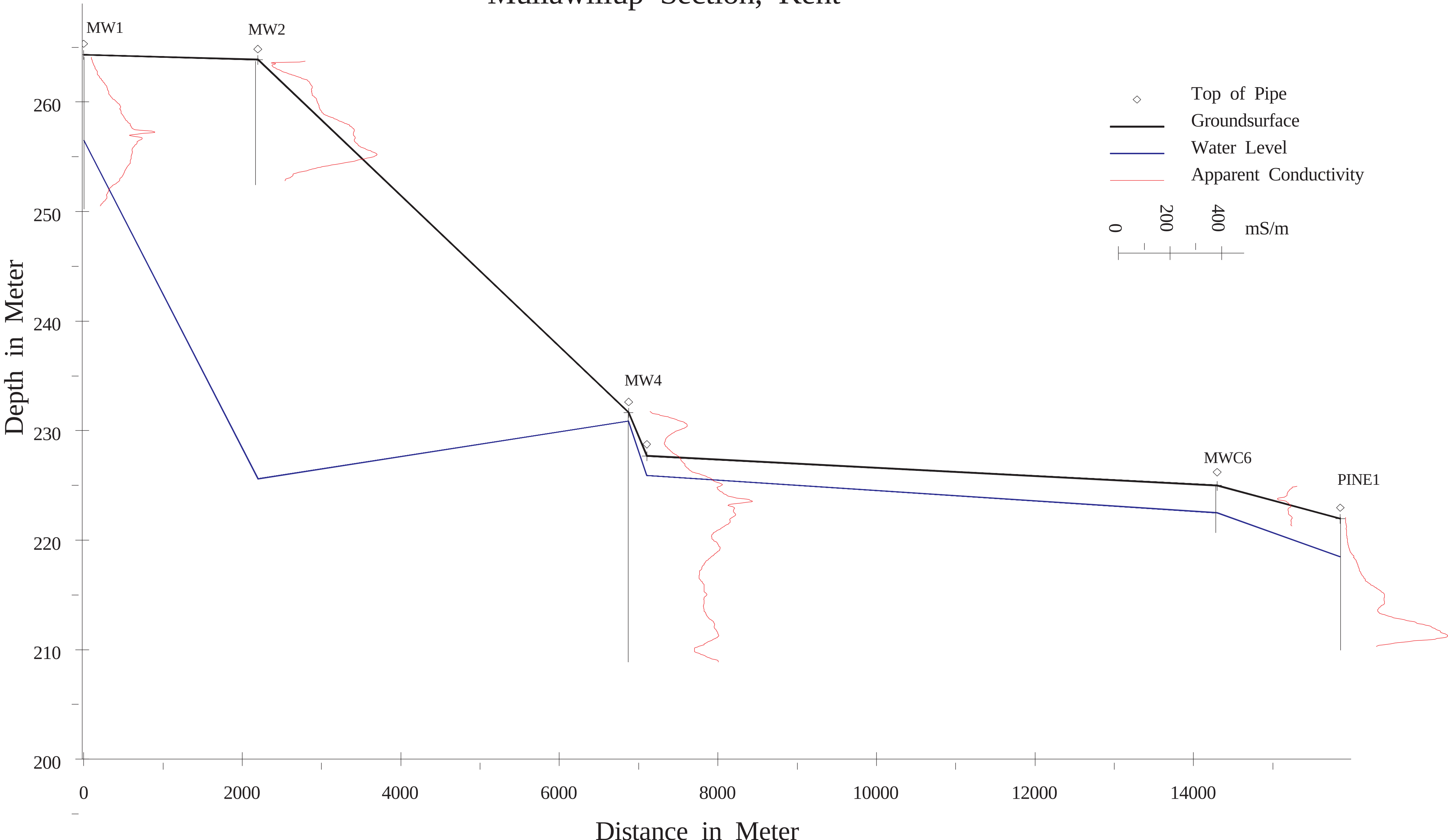
- Low conductivity profiles with conductivity less than 50 mS m^{-1} and increasing slightly below 10 m. The lowest conductivities occur at depths between the surface and 5 m. These profiles were present in the high watershed, steeply undulating areas of the subcatchments in HGU unit U1. (Holes KW8, RG1C, S7, N3, N3C, M1C).
- High conductivity profiles, found in two types. The first is a single bulge profile with peak conductivity >200 mS m^{-1} though some peaks exceed 500 mS m^{-1}. Peaks are usually located at ≈15 m depth. This type of profile is usually found in gently sloping areas of the undulating country of HGU unit U2 (holes N1C, KW3, K5, K4). The second type is a single bulge profile with peak conductivity ranging from 200 to 300 mS m^{-1}, though some profiles do not exceeding 100 mS m^{-1}. These profiles occur in gently undulating country with HGU unit U2 (holes S5, S6, RG2).
- High conductivity profile, with an ill-defined bulge profile. The conductivity varies according to the position of the hole in the lower undulating country with HGU unit U3.
- Profiles with a sharp bulge and conductivity exceeding 500 mS m^{-1} are usually located at the break of slope between HGU units U3 and R1 (hole K3).

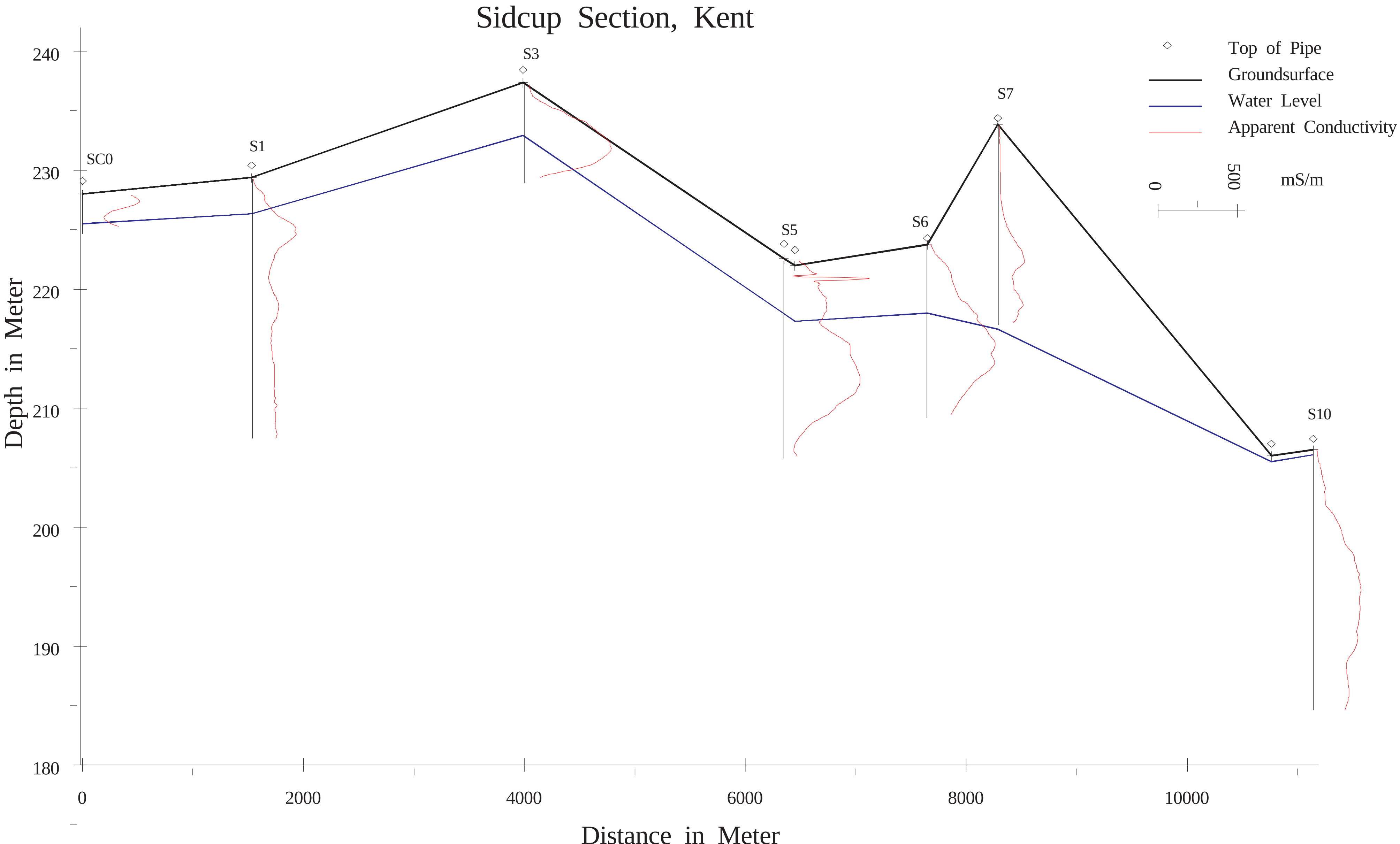
  Double bulge profiles with conductivity increasing with depth, with the lower bulge higher in conductivity. These profiles are usually encountered in flat and lake HGU units F and L. The conductivity usually increases towards the central part of the Lake or Flat HGU unit. Profiles in flat areas have a high conductivity wedge near the surface indicating a possible discharge pattern.

Rocky Gully Section, Kent

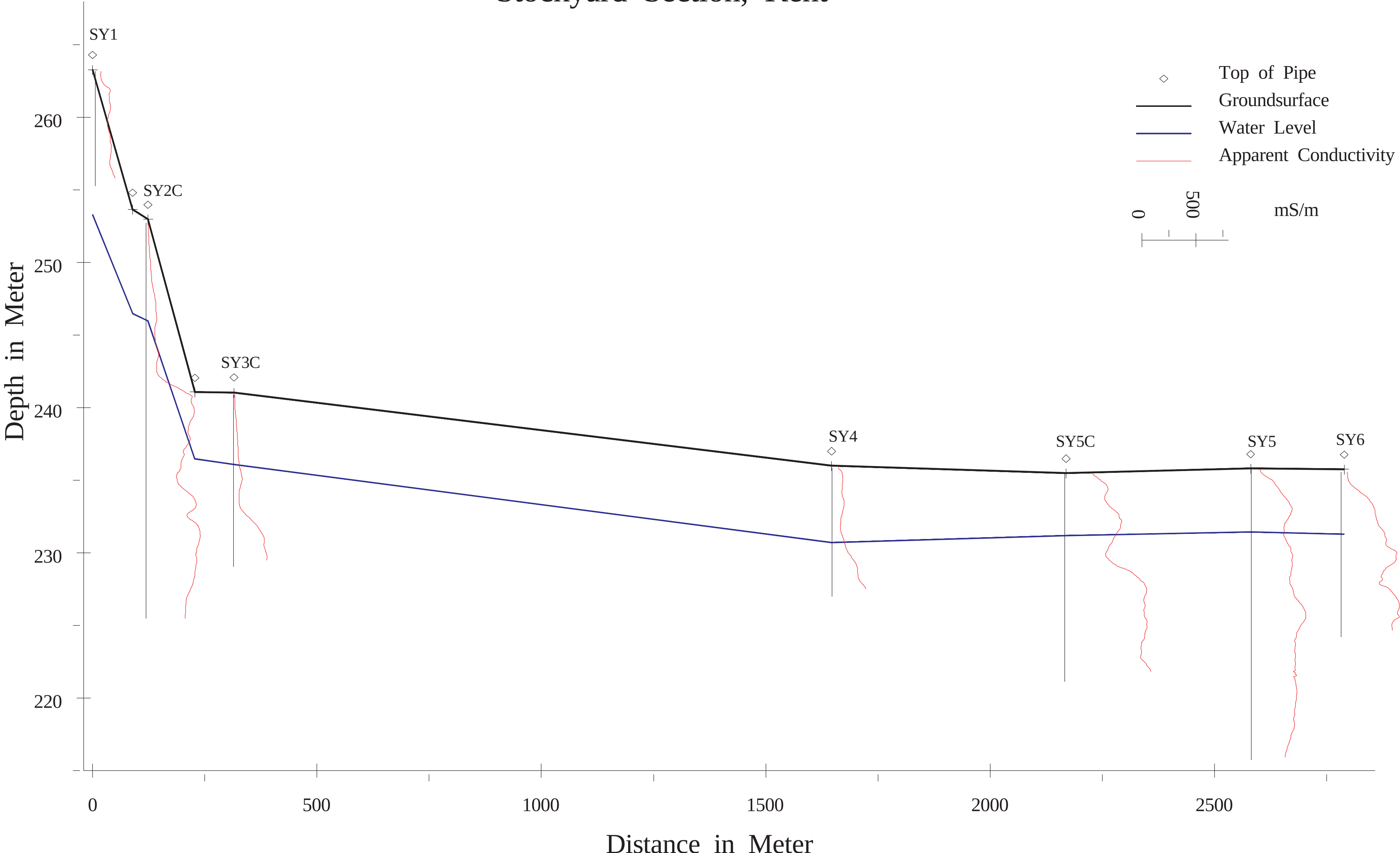


Mullawillup Section, Kent

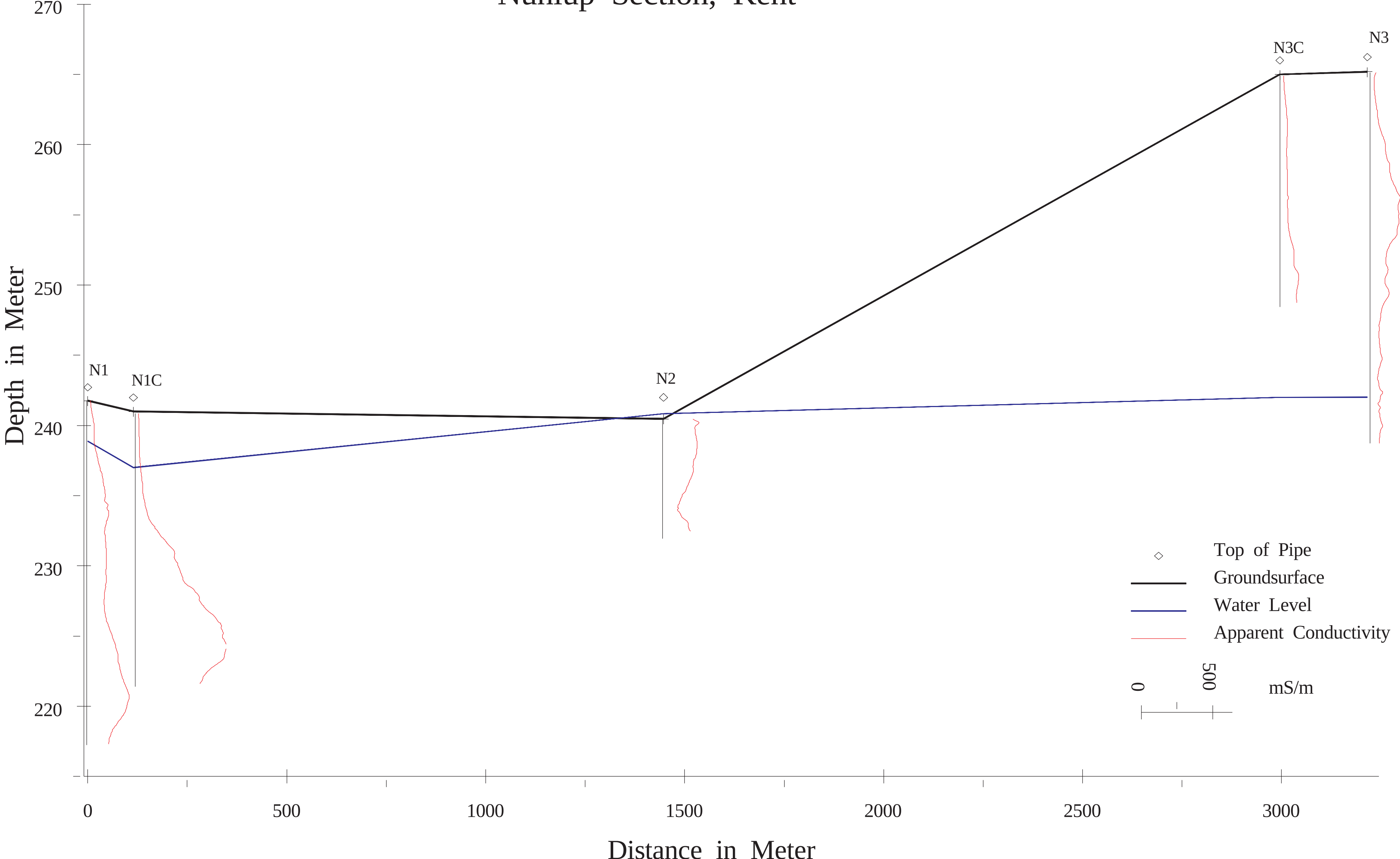



Sidcup Section, Kent
Top of Pipe
Groundsurface
Water Level
Apparent Conductivity
0
500
mS/m
SC0
S1
S3
S5
S6
S7
S10
240
230
220
210
200
190
180
Depth in Meter
0
2000
4000
6000
8000
10000
Distance in Meter

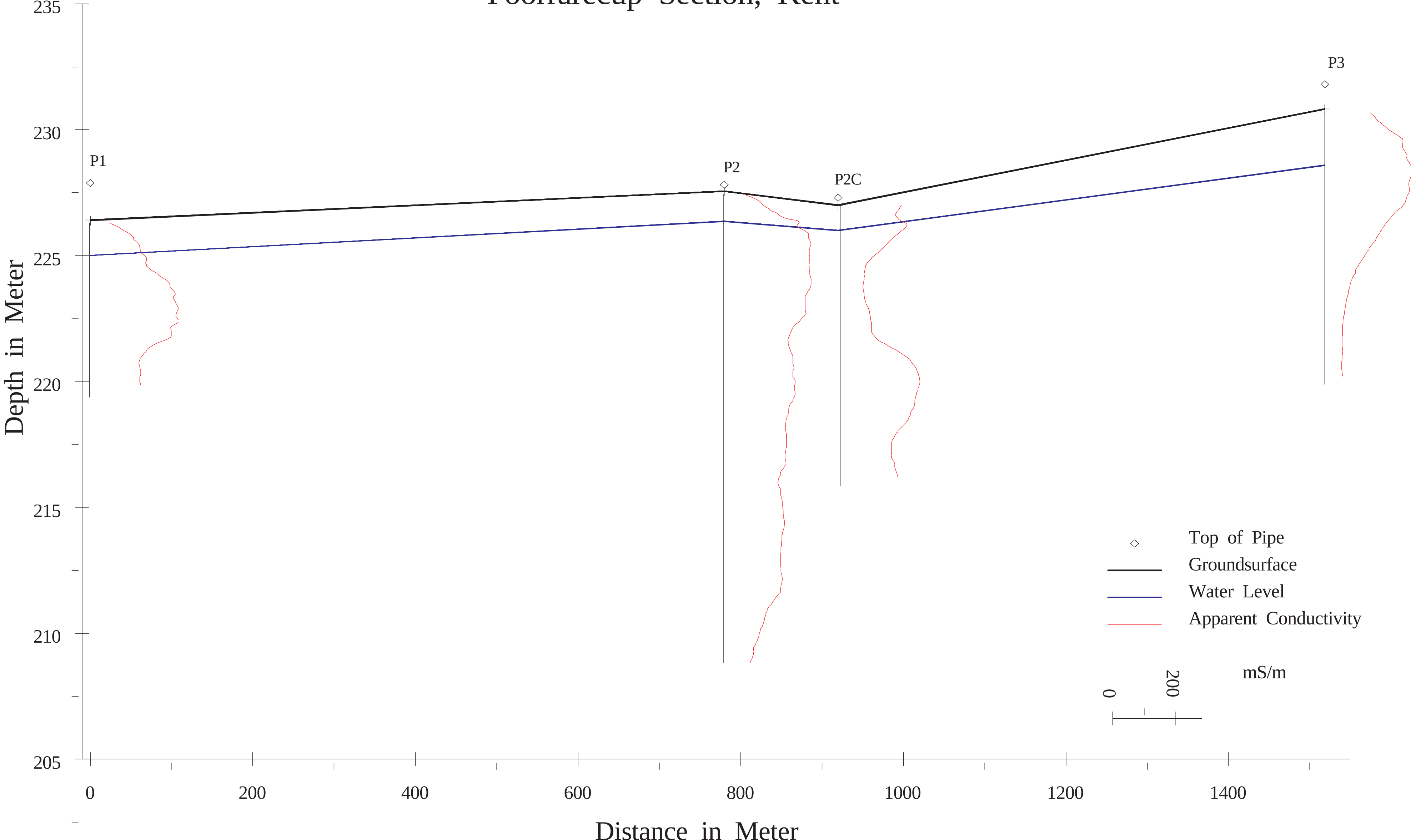
Stockyard Section, Kent



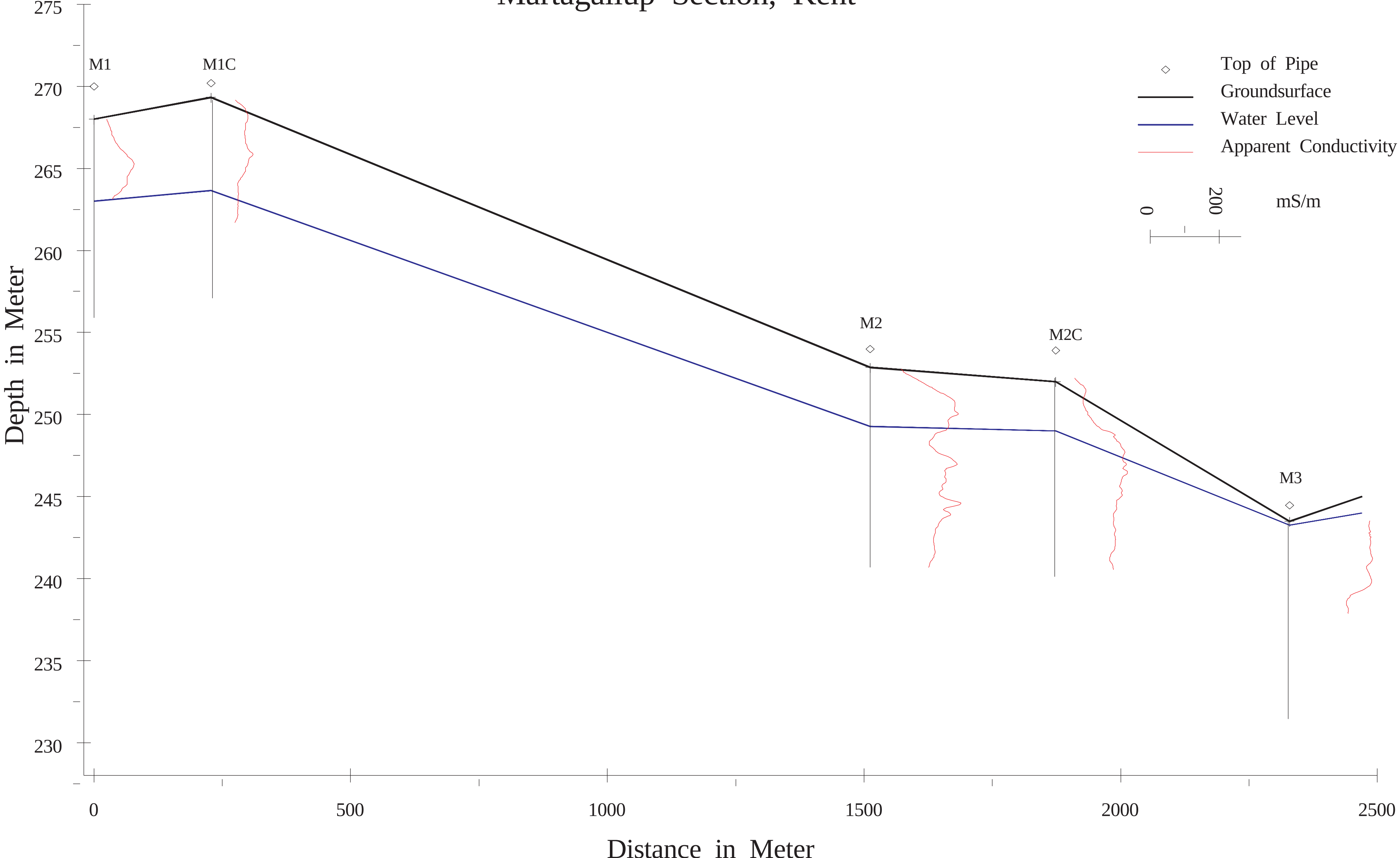
Nuniup Section, Kent

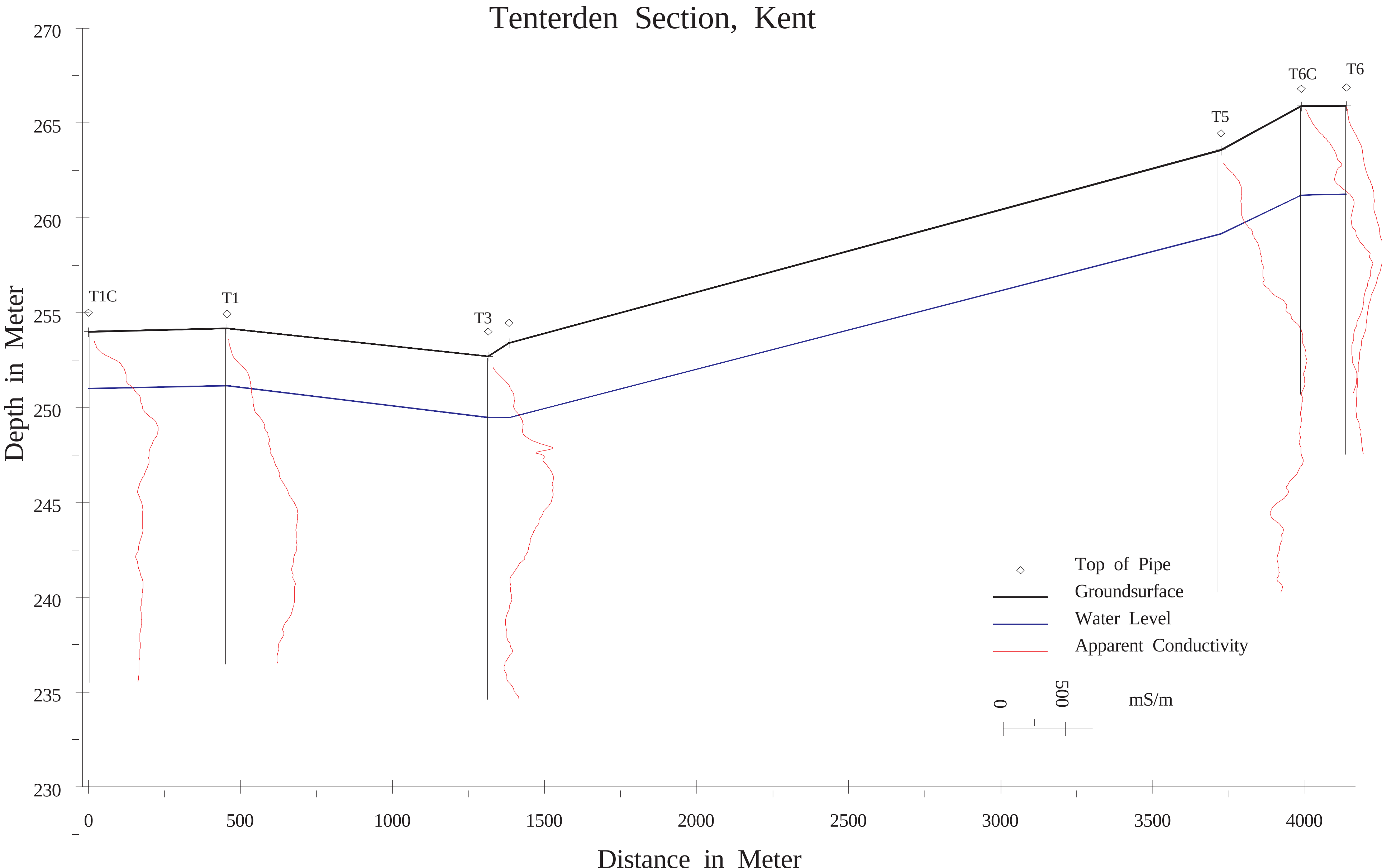


Poorrarecup Section, Kent

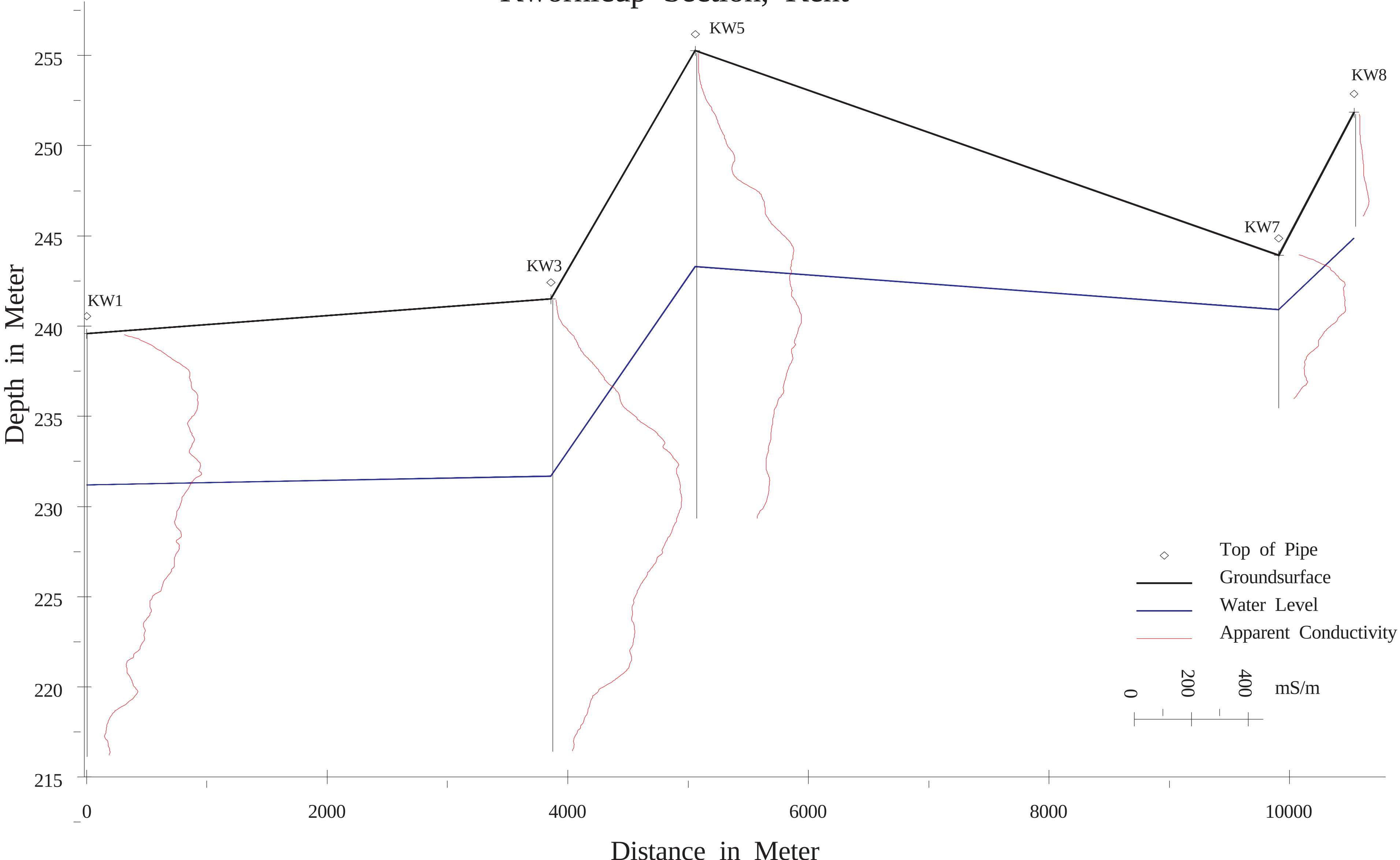


Martagallup Section, Kent

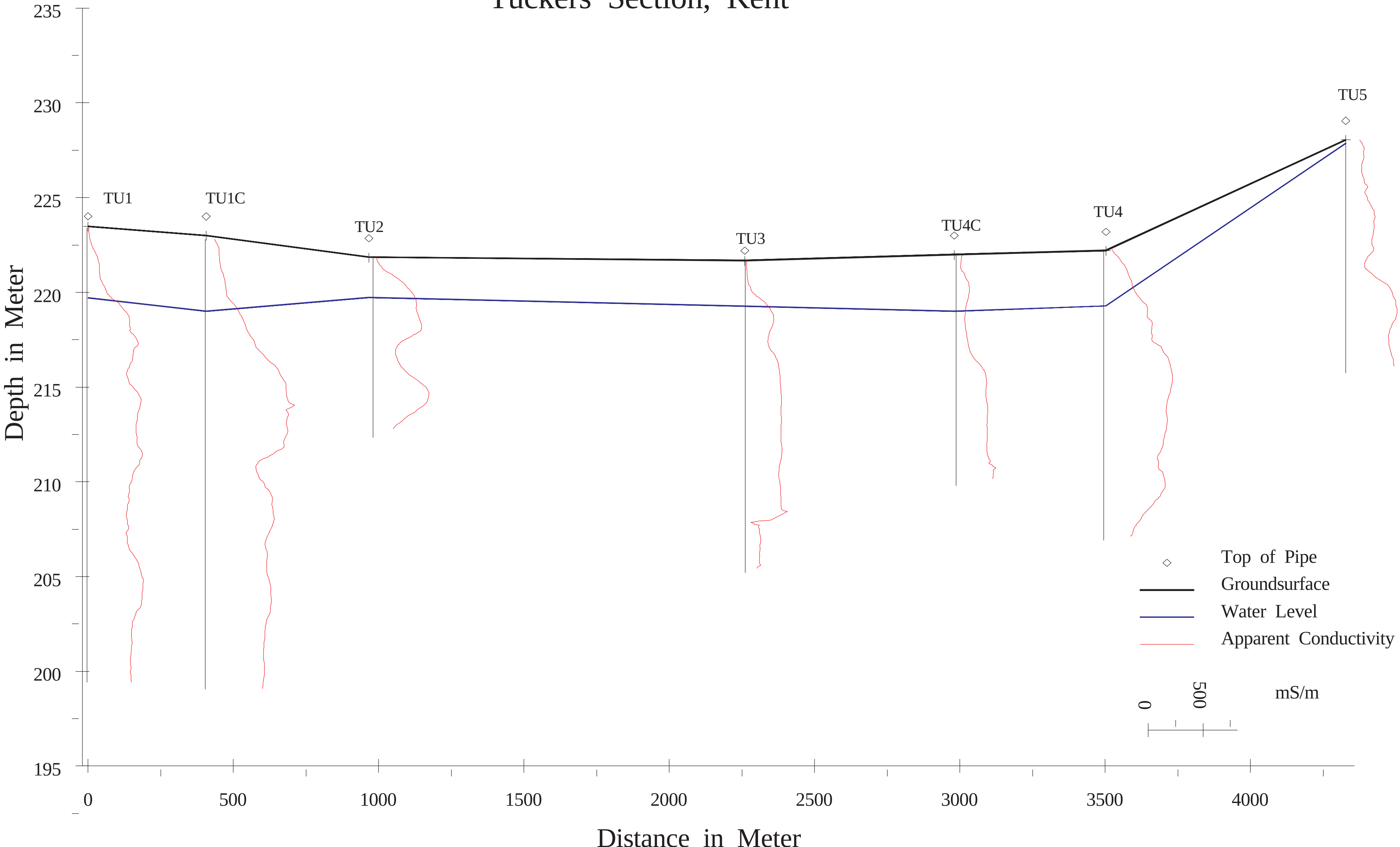


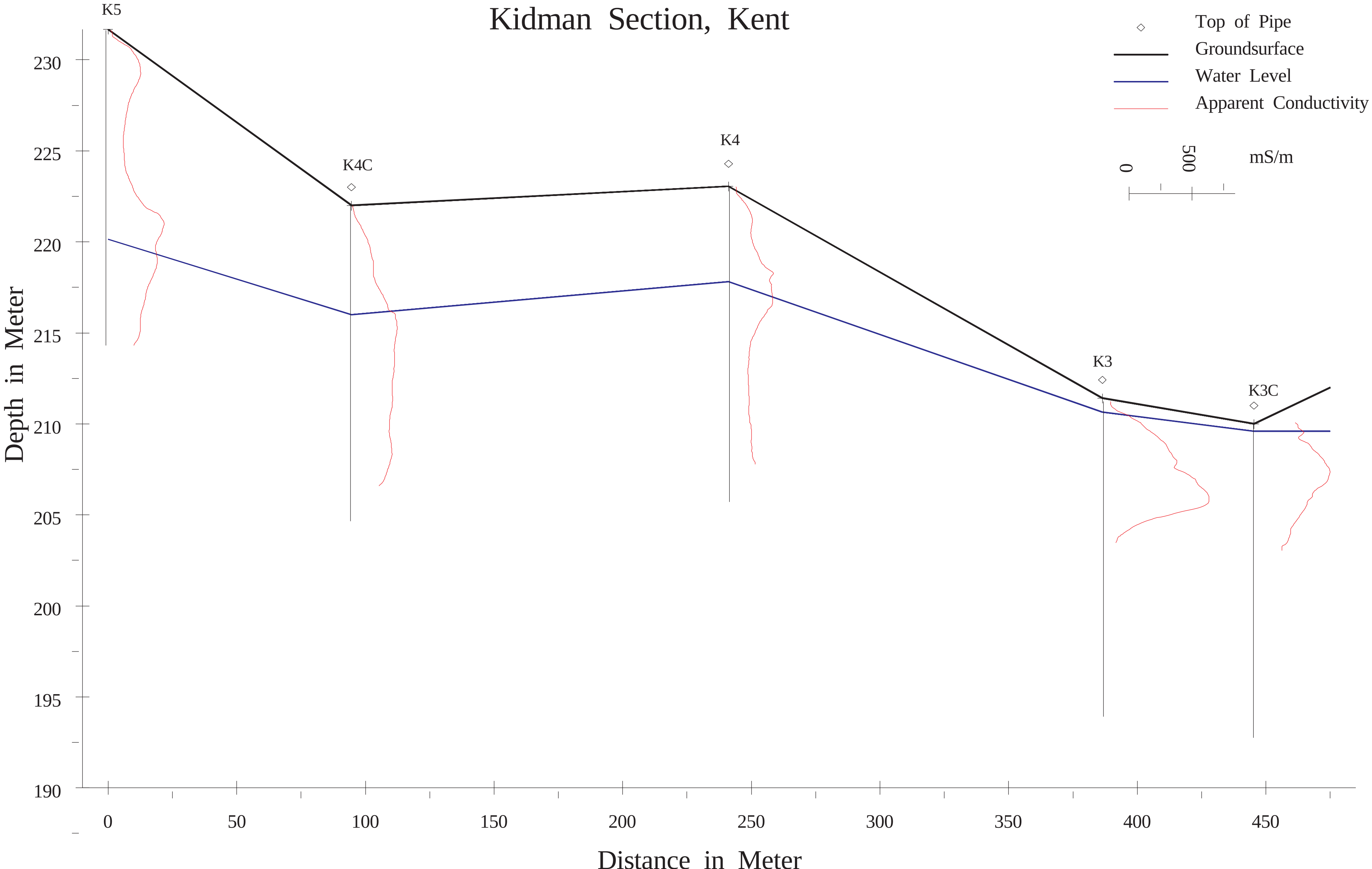

Tenterden Section, Kent
Depth in Meter
270
265
260
255
250
245
240
235
230
Distance in Meter
0
500
1000
1500
2000
2500
3000
3500
4000
T1C
T1
T3
T5
T6C
T6
◇ Top of Pipe
Groundsurface
Water Level
Apparent Conductivity
0
500
mS/m

Kwornicup Section, Kent



Tuckers Section, Kent




Kidman Section, Kent
K5
K4C
K4
K3
K3C
Top of Pipe
Groundsurface
Water Level
Apparent Conductivity
0
500
mS/m
Depth in Meter
230
225
220
215
210
205
200
195
190
Distance in Meter
0
50
100
150
200
250
300
350
400
450

The electrical conductivity profiles were found to be well correlated with the TSS concentration of the cored samples in the locations with weathered profiles. However, in the sedimentary formations, alluvial sediments, and especially in the lakes areas where a high percentage of coal was present, the profile relationship was not as good.

It has been established that the effects of the matrix conductivity on the electrical conductivity response varies with both conductivity of water in soil and conductivity of the clay mineral in the soil in accordance with the equation (Vinegar and Waxman, 1984):

$$\sigma_a = \sigma_w \phi^m + \sigma(\text{clay})$$

where σ_a is apparent electrical conductivity, σ_w is electrical conductivity of water in soil, ϕ is porosity, and m is an exponent.

Consequently, the measured apparent electrical conductivity may be responding to salt content of soil water or clay type. For example, lake deposits have a relatively high apparent conductivity but a comparatively low salt storage. The high conductivity is mainly due to high porosity and the percentage of conductive matrix (clays, lignite and/or coal). However, similar high conductivity in weathered profiles is generally caused by a relatively high salt storage, because the soil material is formed of a lower percentage of conductive material and is usually of lower porosity (Salama et al., 1994a).

Airborne Electromagnetic Survey

A QUESTEM aerial survey had been carried out in the Kent-Frankland region by World Geoscience encouraged by support from a number of farm managers in the region. The apparent conductance was derived from QUESTEM channels 1 and 2 (Figure. 11). The apparent conductance is the apparent electrical conductivity multiplied by the thickness of the conductive layer. The conductance varies from 0 to 15 Siemen metre (S m).

Due to the difficulty in resolving the QUESTEM data, the area has been divided into three zones only (Knapton, 1994). The low conductance zone (<4 S m) extends and covers the high parts of the landscape. The middle conductance zone (4 to 7 S m) covers the midslope areas between the low-lying grounds and the high lands. The high conductance zone (>7 S m) covers the lakes system and the low-lying areas along the streams.

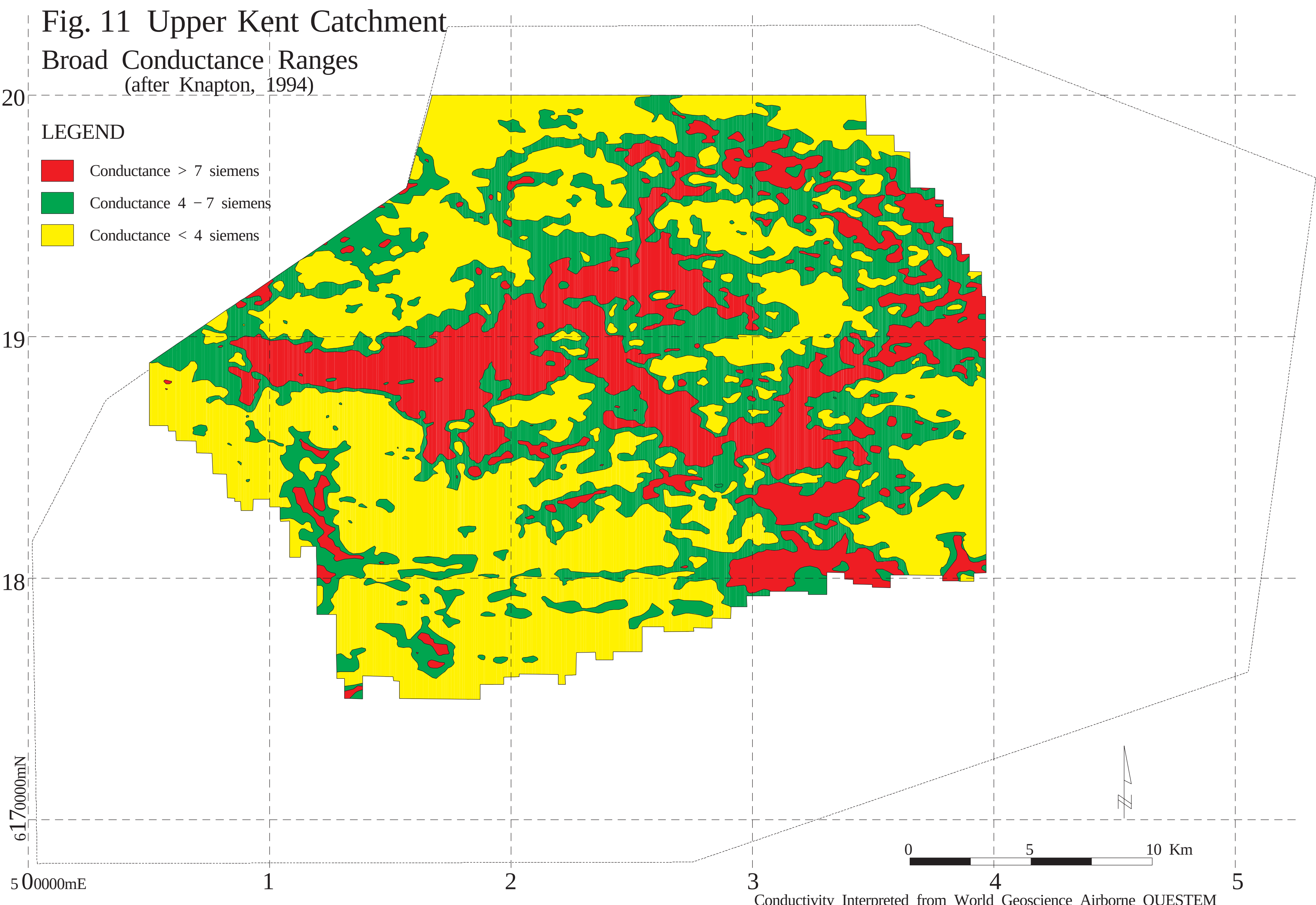
Salt distribution from cores and groundwater.

The average salt storage for each of the hydrogeomorphic units does not show wide variations, from a minimum of 2.1 kg m^{-2} in the undulating HGU’s (U1-U3) to a maximum of 3.5 kg m^{-2} in the lakes HGU’s (L1-L3), as shown in Table 7. However, there are wide variations in salt storage within individual HGU’s. In the undulating HGU group the salt storage ranges from a minimum of 0.5 kg m^{-2} to a maximum of 2.5 kg m^{-2}, whereas in the lakes units it ranges from 1.5 to 6.7 kg m^{-2} .

Fig. 11 Upper Kent Catchment

Broad Conductance Ranges

(after Knapton, 1994)



Conductivity Interpreted from World Geoscience Airborne QUESTEM

Groundwater chemistry (TSS) shows a relatively poor correlation ($r^2 = 0.4$) with salt stored in the landscape. Similarly, a poor relationship is found with the maximum recorded conductivity based on EM-39 measurements. The comparison of the resistivity profiles with the downhole conductivity profiles (EM-39) showed good correlation (Knapton, 1994). In general, the depth to the resistive basement correlates well with known rock depth and is correct to within a couple of metres. Depth to the conductive layer (bulge) is also well resolved and the conductivity of the conductive layer shows good correlation. However, the resistivity of the upper near surface, resistive layer is poorly resolved.

The HGU's in the upper parts of the landscape (eg U1) are characterised by low salt content in the cores and lower electrical conductivity in the groundwater. The resistivity profiles are electromagnetic profiles usually of Types A and B. In these areas, salt is leached away from the soil and does not accumulate below the unsaturated zone in the aquifers due to the steep gradients and relatively faster movement of groundwater. This movement is caused by high permeability resulting from the removal of fine soil particles to lower parts of the landscape during profile development. All this indicates continuous recharge and transmission of water to the lower parts of the landscape.

The HGUs in the middle parts of the catchment (eg U2, U3, P1) are characterised by higher salt storage showing a high conductivity bulge profile occurring mainly in the unsaturated zone. The groundwater shows relatively higher electrical conductivity and the resistivity profiles are usually Types B_1 and B_2. These features indicate areas of slower movement of groundwater allowing salt to accumulate. These features suggest a relatively lower recharge than in the higher parts of the catchment.

The lower parts of the landscape are characterised by higher salt storage and even higher electrical conductivity in the groundwater. Resistivity profile are Types C and D. There is a wedge of high conductivity soil usually found near the soil surface. These features indicate that this part of the landscape is an area of groundwater discharge, with salt concentration through the evaporative process.

DISCUSSION AND CONCLUSIONS

Geology and structures

The geology and geophysical features of the Upper Kent Catchment have a strong control on the hydrogeomorphic units which have been established. The Kent River Catchment is located in the south-western end of the Yilgarn Craton where it interfaces with the north-western part of the Albany–Fraser Geological Province which is formed mainly of gneisses, granitic gneiss, layered gneiss and granitoids (Muhling and Brakel, 1985). Gneissosity and the axes of minor folds in the Albany–Fraser Province generally trend east to east-northeast. The northern boundary of the Province is a shear zone which trends west-northwest and separates granitoids of the Yilgarn Craton to the north from gneisses of the Albany–Fraser Province to the south. The shear zone is associated with a set of faults trending northwest and northeast, some of which lie within the Upper Kent Catchment. The major lineaments (such as the Boyup Fault) follow a southwesterly trend and form the axes of much of the low-lying areas in which most of the marine sediments have been preserved and the significant lakes (eg Porrarecup) formed.

The presence of spongelites and siltstone in the holes drilled in the northern part of the Upper Kent Catchment indicates that marine deposits, belonging to the Pallinup Siltstone, are preserved in the low lands (Lakes HGU). The presence of brown coal indicates that the lower part of the deposits are part of the Werillup formation. These have been deposited in marginal marine coastal swamps and local deltas. The brown coal in the northern part of the Upper Kent Catchment indicates deposition in fluvial and backswamp environments on low-gradient surfaces within extensive pre-existing dendritic drainage systems (Hocking, 1990). The valleys are also characterised by the presence of thick alluvial sediments.

Two major dykes extend in a northerly direction in the central and western parts of the catchment and seem to cross most of the faults and shear zones, indicating that they are younger in age. The displacement of the Boyup Fault by the east–west faults and shears indicate also that it is younger in age. The two set of faults and shears have created graben-type depressions along which most of the sediments have been deposited. The marine sediments were preserved in these depressions. Preferential weathering took place along these lineaments and drainage lines developed along them.

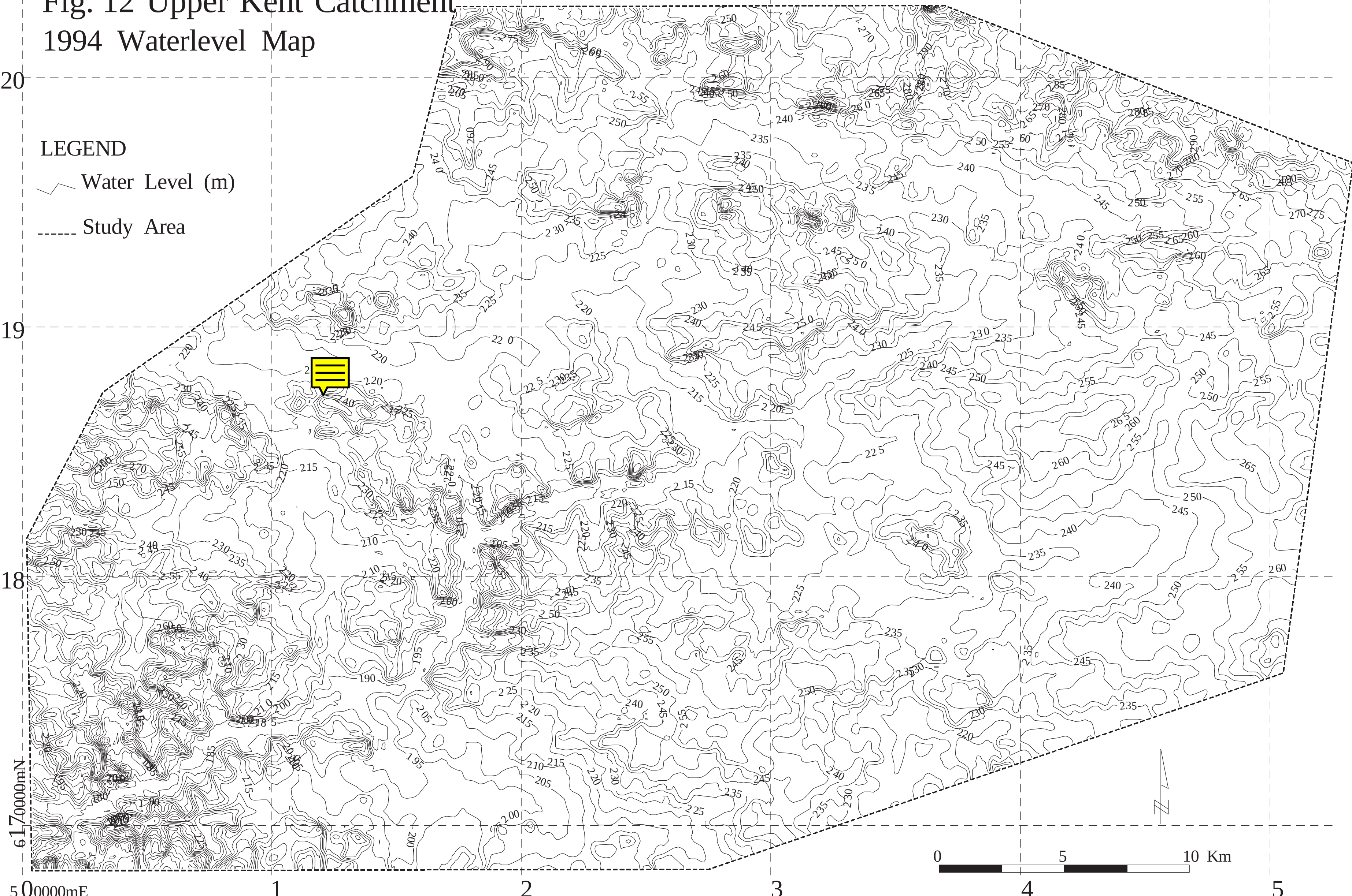
Hydrogeomorphology

The distribution of the HGU’s in the catchment is controlled by the geological formations on which they have developed. The weathering characteristics of each of the geological formations have led to the development of a specific HGU. Flats (F1-F3) have developed in the metasediments in the eastern part of the catchment. Lakes (L1-L3) have developed along depressions created by the fault systems. Gently undulating hills have developed in the northern granitic areas of the Yilgarn Craton, while rugged undulating hills developed on the gneissic rocks of the Albany-Fraser Province.

Relationship between the hydrogeomorphic units and the hydrogeology of the catchment

The regional pattern of groundwater movement is from the high undulating areas towards the lowland. The distribution of water-level contours (Figure. 12) indicates that groundwater is stagnant in the flat areas of the landscape. The break of slope is a significant topographical

Fig. 12 Upper Kent Catchment
1994 Waterlevel Map



feature which controls where groundwater discharge will take place. Prior to clearing, it may be assumed that the water levels were low and the groundwater recharge was very small. This scenario was altered by clearing with the result that the water levels have risen, in some areas near to the soil surface, transmissivities have increased and new aquifers developed. Consequently, groundwater discharge has occurred when and where the transmitting capacity of the aquifers has been exceeded. This occurs primarily in locations where the hydrogeomorphological characteristics change. Water levels are found near the surface at the change of slope between sub-units (U1/U2/U3) within each HGU and, more noticeably, at the change of slope between two different HGU's (especially with the U3/R1 transition.

Groundwater levels are deep in the undulating HGU's (eg U1), but near the surface in all flats (F1-F3) and morass (L3) and lowland areas of the landscape. Depth to groundwater levels decrease from higher to lower elevations in the landscape.

Salt distribution

The results of the electrical conductivity analyses of the cored holes, indicate that salt storage is high in the morass (L3), flats (F1-F3) and lowland (L2) areas of the landscape. Salt storage decreases with an increase in elevation and for areas of steeper slope. Salt storage can be classified from the highest to the lowest in the sequence of geological units: from marine sediments, alluvial, metasediments, granites and gneisses. The undulating HGUs have the lowest salt storage, though storage increases from U1 to U2 to U3, that is, from higher to lower position in the slope. Salt storages have been found to be very high at the break of slope between the U3 and R1 zones. Although the lakes units (L1-L3) have the highest conductance of all HGUs with conductance increasing towards the central part of the unit, the salt storage is comparable with that in the flats (F1-F3) and the lower parts of the undulating units (U3).

The hydrogeological regime, which is itself a result of the geologic and hydrogeomorphic configuration of the catchment, has the following characteristics:

1. Relatively high recharge in the higher parts of the landscape, with recharge decreasing downgradient.

2. Discharge is mainly along the break of slope, around the lakes, along the streams and at the break of slope where this involves a change in HGU (such as at the contact between U3 and R1 units).

3. Salt accumulates in the discharge areas primarily located in the stagnant flats (Units F2 and F3) and in the morass area (Unit L3).

4. In the low-lying areas high porosity, high water content, and high percentage of clays and organic material, may result in relatively high conductance can be interpreted incorrectly as high salt content. However, relatively high salt content has been measured in the elevated areas of the lakes and slightly less salt in the low-lying areas of the lakes.

The roles of hydrogeomorphology, geology and geological structures on groundwater discharge

The primary role of the geological structures is in controlling solute migration and mineral deposition during the initial weathering process. The structures define the erosion, transport and sedimentation routes in the area. They also play a primary role in defining major rivers and streams in the area as water tends to follow lines of weakness in the landscape. For example, in the Upper Kent River catchment, the river course follows the major fault which is extending in an east–west direction. The lakes were formed in the depressions created by the crisscrossing faults where the marine deposits were preserved in graben type formations.

The role of the geological structures in groundwater movement in the Yilgarn Craton and the Albany Fraser Oregon has been overemphasised by Engel et al. (1987), Salama et al. (1993c), and Ferdowsian and Greenham (1992). The question needs to be asked whether geological structures and shear zones actually play the primary or secondary role in the location of salinity development. All the evidence from the analysis of water-level patterns in the wheatbelt of Western Australia (Salama et al., 1991, 1993b, Salama and Bartle 1995), and in NSW, indicates that the structures play the secondary role and that the hydrogeomorphological and topographic controls play the primary role (Salama et al., 1996a).

Groundwater discharge will take place in low-lying areas of the landscape with or without the presence of geological structures. The main effect of the presence of geological structures in the lower part of the landscape is to increase the salinity of the groundwater up-slope of the structures due to the impact of evaporative concentration on salt accumulation (Salama et al., 1994a).

The palaeo Kent River and the palaeo lake system

Previous studies of geomorphic evolution in the southwest of Western Australia (Fairbridge and Finkl, 1978) disclosed the several stages of river development as being piracy, change of direction and evolution. These included Permian trends flowing towards the northwest, Mesozoic trends towards the west and Eocene trends flowing southward. All these trends have been caused by the tectonic activities which previously affected the Australian continent. The Eocene separation of Australia from Antarctica led to a marginal upwarp developing along the south coast and forming the Ravensthorpe Drainage System, involving much stream piracy and the replacement of the northwesterly trends by southern directions (Fairbridge and Finkl, 1978).

The Upper Kent River catchment is in the boundary of the Jarrahwood axis which separates the northern and northwestern flowing systems from the southern ones. The northern area of the Upper Kent catchment does not seem to have been affected by the upwarp and parts of it remained flat. The development of the Kent River in this area was, to a great extent, following the east–west lineaments, with the southern uplifted areas damming its course and causing the formation of the numerous lakes and the internally drained basins. The river does not start to have a regular course until after the falls in Millers Basin. The uplift of the southern area caused the river to make major changes to its course and take a right-angle turn towards the south.

The contact between the porphyritic granitoids (with their major lineament trending southwest) and the gneiss (with its major lineament trending southeast) in the Albany–Fraser Oregon (Myers, 1990) controls the course of the Kent River and the sharp southeasterly bend south of Rock Gully.

The distribution of the lakes, flats, and sediments along an east–west axis on the northern part of the catchment indicate the possibility of a palaeo-river occupying a line parallel to the existing Kent River in this part of the catchment. This valley has been filled with marine sediments during the gradual sea transgression which drowned the drainage system in the late Eocene. This period of marine deposition is preserved in the lakes area. Most of these sediments are of the Middle to Late Eocene Plantagenet group (Hocking, 1990).

The distribution of lakes at the different elevation levels along structural lineaments, together with the presence of brown coal, indicates that these lakes have occupied the same location since the Eocene. They are primarily located on the northern side of the Kent River. These lake areas are now acting as groundwater discharge zones associated with the groundwater levels which have been rising since clearing. Many of the lakes accumulate water seasonally and others have now become permanent. It would be expected to find shallow groundwater levels associated with these lake features and there is every indication that they are within hydraulically closed sub-basins. This latter feature, plus the change in climatic conditions and the increasing volume of groundwater discharge to these depressions, may all contribute to the observation that they are areas where salinity is increasing.

It is important that future management options for the control of salinity in the Upper Kent River catchment take into account the palaeo history of the river and lakes.

Inundation

By definition, areas prone to inundation and water logging are flat areas with either little or no gradient and no well-defined channels or streams. The sluggish gradient of the streams, the break-up in stream connectivity between flat areas and the presence of wide swamps and lakes are all indications that a high percentage of the Kent River catchment is prone to inundation.

A modified geomorphic classification of the catchment which takes into account the gentle slopes has been prepared to establish the risk of inundation (Table 9). The morass areas (L3) in the Upper Kent catchment, with a slope less than 0.01, have the highest risk factor. The flats (F1-F3) have very high to high risk, and the other areas of the catchment have low to no risk. The high percentage of the flats (F1-F3 occupy 25%) in the catchment indicates that most of the surface water and groundwater problems cannot be solved except by improving the drainage out of these areas.

Table 9: Identification of areas at risk from inundation based on hydrogeomorphic units and slope criteria.

Hydrogeomorphic Unit			**Slope Range in degrees**	**Inundation Risk**	**% Area**
Description	**Tech. 1**	**Tech. 3**			
Morass	L3		<0.01	very high - annual	0.1
Flats	F1-F3		0.01 - 0.6	very high - high	25
Very gently inclined	P3	V3	0.6 - 1.0	high - moderate	18
Gently inclined	P1, P2, U3	V2, V3, G3	1.0 - 3.0	moderate - low	39
Moderately inclined	U2	G2, G1	3.0 - 5.0	very low - never	10
Hilly	U1		> 5	never	2

Groundwater discharge areas

Groundwater discharge tends to be located in lower parts of the landscape, which are equally prone to inundation. It is well established that low-lying areas, swamps and lakes are natural groundwater discharge areas. Certain areas, where the groundwater conditions are suitable and hydraulic conductivities are high, can behave seasonally as either recharge or discharge areas, or as both discharge and transmission areas. In the Upper Kent catchment, in areas where both hydraulic conductivities and gradients are low, the transmission process is very diminished so that only groundwater discharge occurs.

Groundwater discharge also takes place in areas with a break of slope and convex curvature (discussed in detail in Salama et al., 1996b, 1997). It has been found that the specific location of this discharge can only be properly delineated by using the relationship between groundwater levels and surface elevation (Figure. 12). Areas of groundwater discharge can also be delineated by analysing the convergence of groundwater flow lines, change in gradients and the intersection of the groundwater contours with topographic features such as surface streams, lakes, depression or low-lying areas (Salama et al., 1996b & c).

Hydrologic predictions and risk factor

Depth to groundwater is greater in the upper parts of the landscape than in the flats and the lakes of the areas of lower elevation. The long term water-level pattern (McFarlane et al., 1994) indicates that the water levels are rising either monotonically or continuously in the locations measured in the undulating country. Although showing seasonal fluctuations the water levels are generally steady in the lower parts of the landscape. However, continuous monitoring of water levels in the Upper Kent catchment in the two years 1993 to 1995 does not show a continuously rising water level pattern except in 6 wells. This might be due to the abnormally dry seasons in that period.

Assuming the present land management regime will not change appreciably in the next 15 years, and that the longer historic position will continue into the future with groundwater levels rising, several scenarios for water level rise which represents the possible water level patterns were simulated.

A 1994 water level map was produced for the Upper Kent River catchment using the relationship between the water level (WL) measured in 60 wells and the surface elevation (SE) of these wells found to have the regression $WL = 1.824 \times SE^{0.887}$ ($R^2 = 0.97$). The 5 m water level contours were produced using a 100 m grid of a digital elevation model (DEM) having the same contour interval. It must be stressed that the accuracy of the water level contours produced depends upon the accuracy of the DEM from which they are derived. In addition, it must be emphasised that the regional water level maps can only be used for regional planning purposes. If detailed farm scale planning is required, appropriate large scale maps should be prepared using contour interval of at least 1 m.

New water level maps were produced for the Upper Kent River catchment by adding the long term average trend (McFarlane et a., 1994) to the 1994 water level map. The catchment area for each of three different ranges of groundwater level (< 2 m, 2 - 5 m, and > 5 m) were calculated for the year 2010 (Table 10, Figures 13 & 14a, b & c). The results show that, for the worst possible scenario of a rise of 2 m in the high land and 1 m in the lowland, water levels in 65% of the catchment area will be less than 2 m. With a rise of 2 m in the low lands and 1 m in the high lands only 47% of the catchment will have water levels less than 2m.

Fig. 13 Upper Kent Catchment
2010 Waterlevel Map

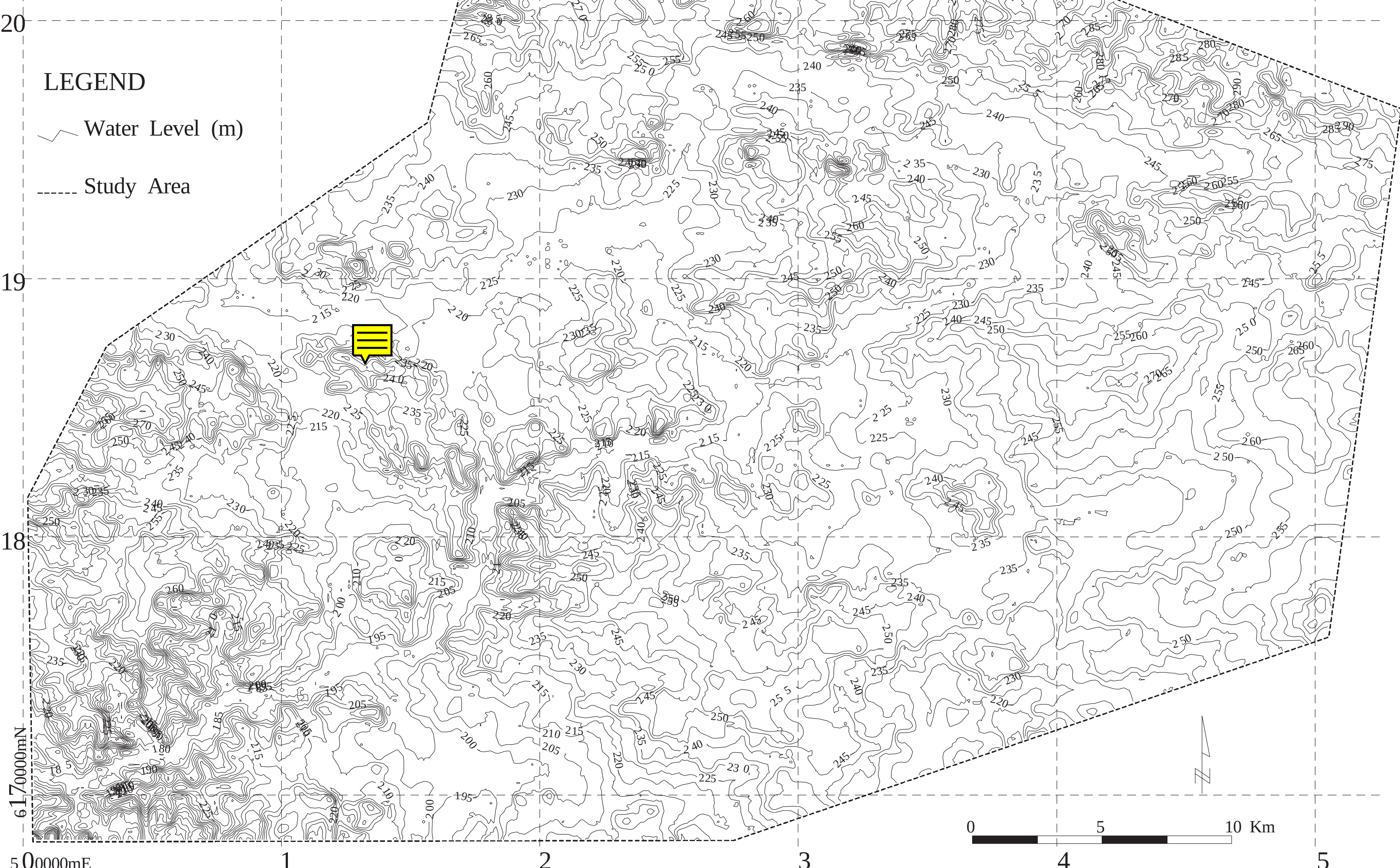


Fig. 14a Upper Kent Catchment

Computed Depth to Groundwater for 1994

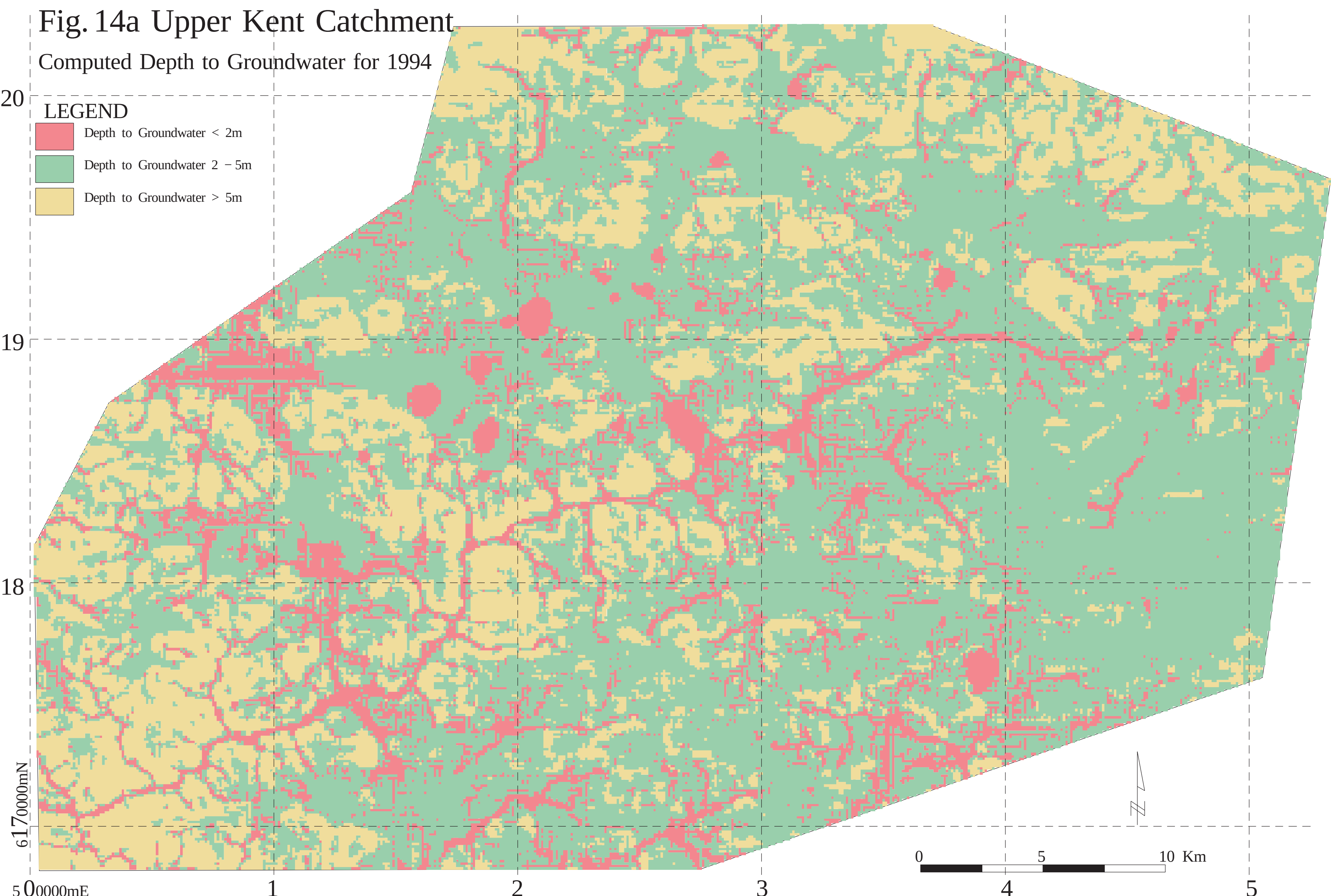


Fig. 14b Upper Kent Catchment

2010 Depth to Groundwater (Scenario A)

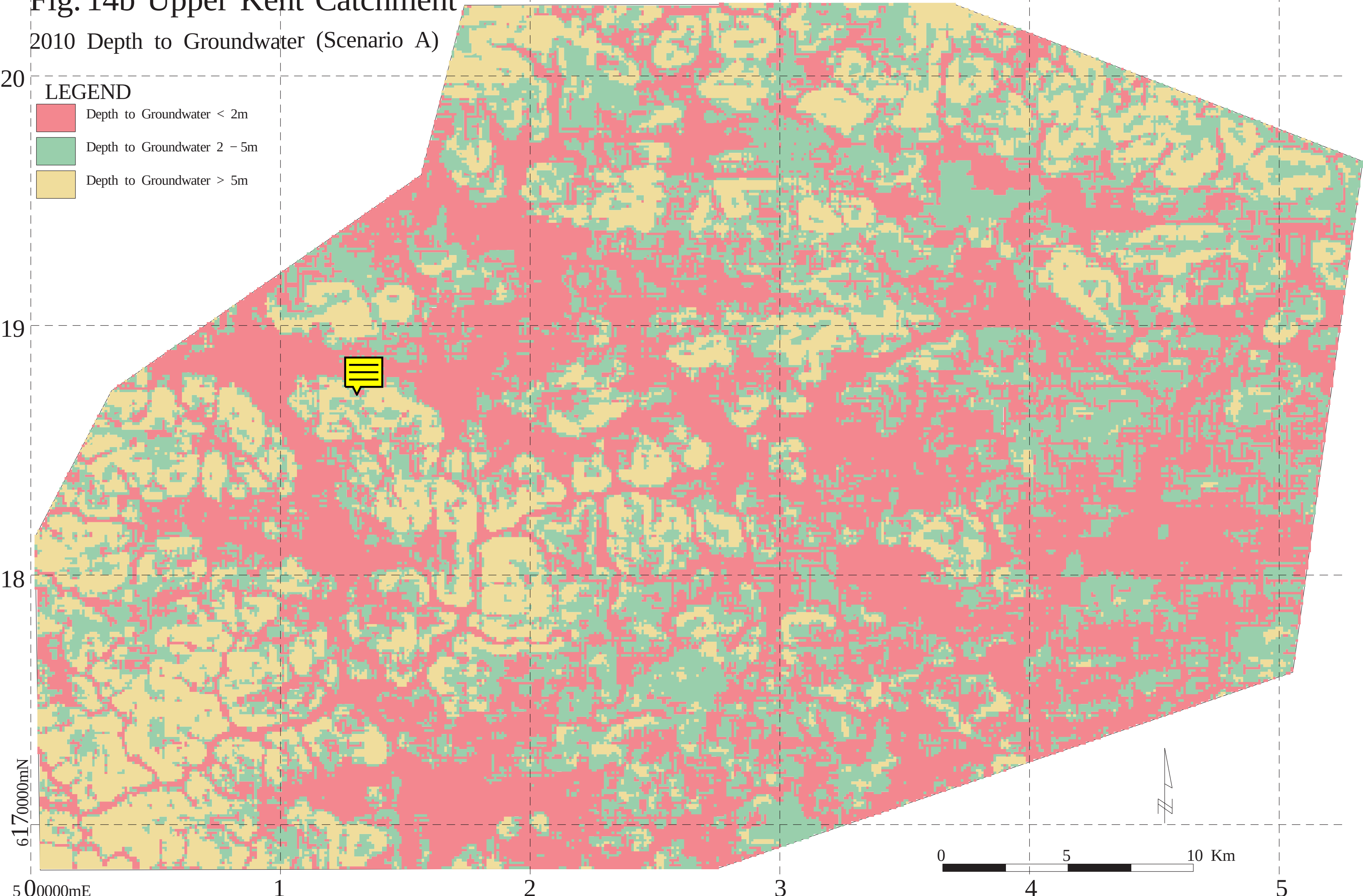


Fig. 14c Upper Kent Catchment

2010 Depth to Groundwater (Scenario B)

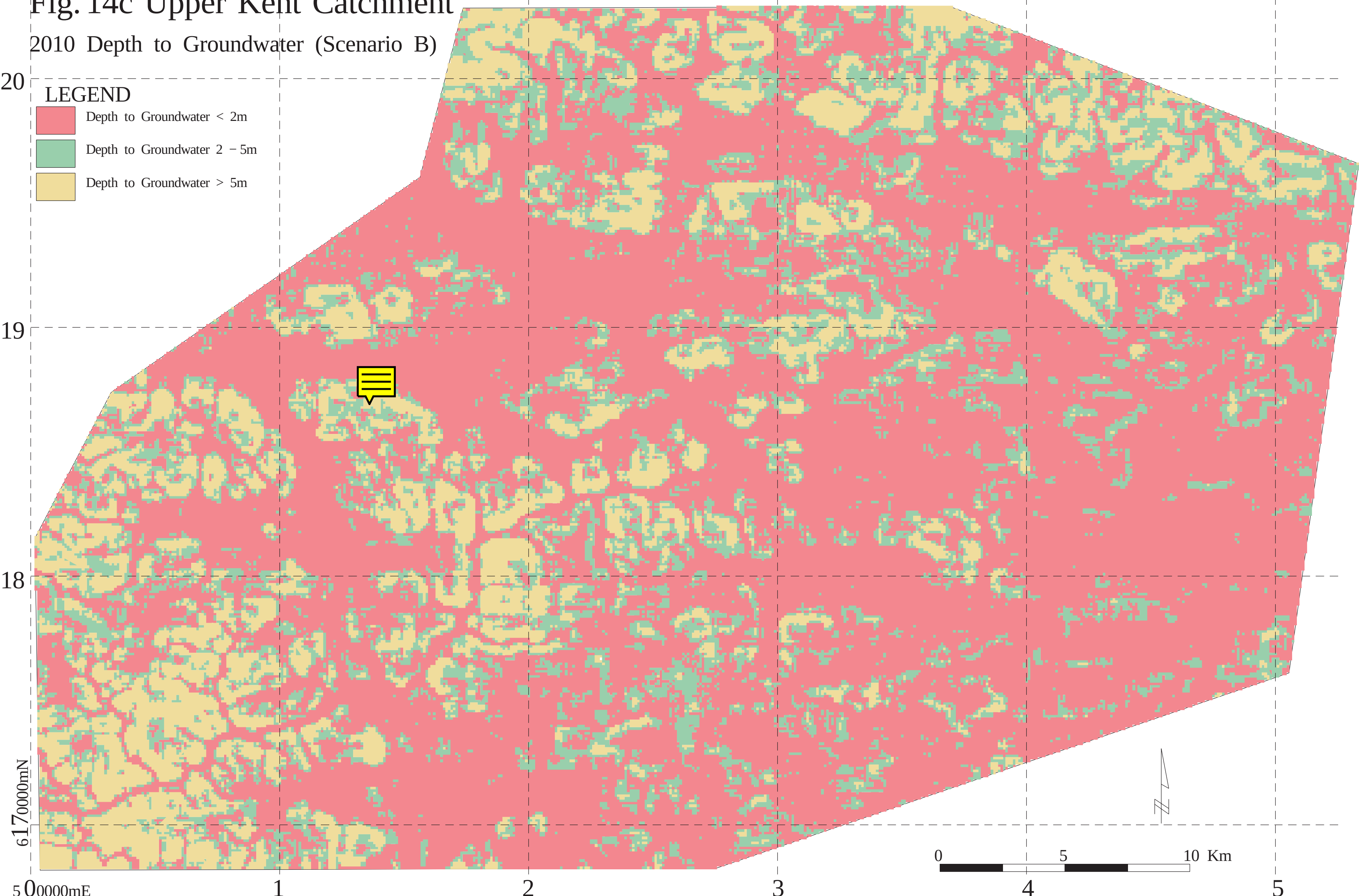


Table 10: Prediction of groundwater level change in the Upper Kent Catchment by the year 2010 assuming two different scenarios.

Depth to groundwater metre	% Area of Catchment 1995	% Area of Catchment 2010 ①	% Area of Catchment 2010
< 2	14	47	65
2 to 5	60	33	19
> 5	26	20	16

Scenarios:

① Water level rise of 1m in the highlands and 2m in the lowlands.
Water level rise of 2m in the highlands and 1 m in the lowlands.

This reinforces the generally accepted position that it is very important to control the rise of water levels in the high lands where the water levels trends indicate continuous rise. Although draining the lowlands will reduce the water levels, if nothing is done in the highlands, a higher proportion of land will be affected.

Conclusions

The new technology of hydrogeomorphological mapping has been shown to be an appropriate tool for identifying the landscape features influencing the salt storage and the location of zones of groundwater recharge and discharge in the Upper Kent catchment. The results of the mapping of these features in the catchment show that the distribution of HGUs is controlled by the geological formations on which they developed. The weathering characteristics of each of the geological formations led to the development of a certain HGU. Flats (F1-F3) developed in the metasediments in the eastern part of the catchment. Lakes (L1-L3) developed along depressions created by the fault systems. Gently undulating hills (U2-U3) developed in the northern granitic areas of the Yilgarn Craton, while rugged undulating hills (U1) developed on the gneissic rocks of the Albany-Fraser Oregon.

The regional pattern of groundwater movement indicates that groundwater moves from the high undulating areas towards the lowland. A method for determining the contours of the groundwater system has been developed and applied to the Upper Kent catchment. The direction of groundwater flow has been determined also which assists in locating areas of recharge and discharge. The distribution of the water-level contours, and their relationship to topographic contours shows that groundwater is stagnant in the flat areas of the landscape. From the relationship of groundwater information to HGUs it has been found that slope, break of slope and curvature control where groundwater discharge will take place. This provides a basis for focussing management to control, or avoid, unacceptable increases in waterlogging and salinity. Groundwater levels have been found to be deep in the undulating areas, and near the surface in all flat and morass areas of the landscape.

The results of the analyses of the cored holes combined with the geophysical measurements, indicate that salt storage is high in the flats and lowland areas of the landscape. Salt storage decreases with an increase in elevation and for steeper slopes. The shape of the salt profiles reflect the historical accumulation of salt before agricultural development and suggest that there has not been a major leaching of salt from the profiles in the toward discharge areas since forest clearing.

The newly developed hydrogeomorphic unit (HGU) technology is a robust tool which has been used successfully to classify areas with similar hydrological and hydrogeological features in the Kent Catchment. The hydrogeomorphic units have been found to be useful surrogates for the hydrogeological characterisation of the catchment. Combining this with the technology developed to estimate the groundwater contours in the catchment, it is now possible to determine the location for appropriate management of groundwater recharge and discharge, shallow groundwater levels, and seasonal inundation. Applying this technique to the Upper Kent catchment, it has been estimated that, if present land management is maintained, from 47 to 65% of the catchment will have groundwater levels within 2 m of the soil surface in less than 20 years time (by 2010).

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APPENDIX A

HARSD (Hydrogeomorphic Analysis of Regional Spatial Data)
An approach to hydrogeological characterisation of catchments for landscape classification, groundwater level mapping and flow net modelling.

The suite of procedures for modelling groundwater behaviour known as HARSD (Hydrogeomorphic Analysis of Regional Spatial Data) provides a unique alternative to more traditional land unit mapping and groundwater modelling. It is particularly suited to regional applications in the absence of detailed hydrogeological description. Contained in the bibliography at the end of this appendix are papers which describe the theory, techniques and automated GIS procedures involved in classifying the landscape into hydrogeomorphic units and the subsequent inference of the hydraulic head surface for input into a groundwater flow model such as FLOWNET. Like any computer-based spatial inferencing system, the publication of a series of scientific papers cannot accommodate the level of detail necessary to fully explain the precise steps and logic in such a way that the work is in practice repeatable by others. However, the CSIRO Division of Water Resources Technical Memorandum 96/27 by Salama, Hatton and Dawes (1996) provides a level of detail which draws together the features of the technology. The text of this appendix is an extended extract from that publication.

HARSD is actually a suite of procedures covering:
- Hydrogeomorphological Classification of Catchments
- GIS and Hydrogeological Methods for Constructing Hydraulic Head Surfaces (HHS)
- Flow Net Analysis (FLOWNET).

These procedures have much in common with other, more traditional groundwater modelling procedures. HARSD is distinct in that geomorphological theory and experience is used to infer the spatial co-dependence among aquifer parameters and other controls on groundwater behaviour. Rather than accepting a parameterisation which demands the independent specification of a number of below-ground parameters in some *a priori* spatial arrangement, the technique is predicated on the assertion that at least in erosional landscapes, surface topography reveals the spatial coevolution of these properties. Combined with some hydrogeological understanding and even very sparse hydrological data, the technique offers a more efficient and constrained parameterisation than traditional continuum-mechanics based groundwater models.

Salama, Ye and Broun.(1996) present the theory and application of constructing hydraulic head surfaces. All groundwater flow models based on continuum mechanics require the specification, *a priori*, of the hydraulic head surface (or, loosely speaking, groundwater levels). The inferencing of such surfaces inevitably relies on sparse point estimates from monitored bores. These levels must be extrapolated across the entire domain by some method.

Standard methods available for manual contouring include: mechanical, parallel, equal-spaced and interpretive contouring as well as several interpolation and stochastic techniques. Preparation of contour maps using these algorithms commonly produce surfaces that project below or above surface contours. Filtering or kriging usually produce a smooth surface map which, in most cases, will intersect surface contours, project over lakes, and cross rivers. Contouring packages often suppress or distort anisotropic trends because interpolation schemes generally assume spatially uniform neighbourhood influences, smooth local transitions across a continuous surface and produce contoured features that could not possibly exist and do not take into consideration the different aspects which control groundwater movement, mainly: hydraulic parameters, gradients, surface contours and breaks of slope.

The key to accurate and efficient groundwater modelling is producing the best estimate of the hydraulic head surface; in the case of HARSD, this becomes input into a steady-state flow net analysis (see Dawes, Hatton and Salama, 1996). The surface estimation procedures associated with HARSD are best presented according to a hierarchy of data availability, for the best approach to hydraulic head surface estimation varies with the density and distribution of spatial data.

Constructing a Hydraulic Head Surface Solely from Elevation Data

In broad-scale groundwater resource assessment work, we are often confronted with the challenge of estimating a hydraulic head surface with very little or no water level data, and no recharge or aquifer data. To proceed, we are forced to make assumptions about the relationships among those terrain features which we can see and map extensively (land cover, elevation), and the groundwater level and aquifer parameters we need to make our inferences.

Digital elevation models (DEMs) are a good data source to base the above inferential relationships; three reasons for this are:

- Digital elevation data are becoming increasingly available.
- It is easier to integrate landform information represented digitally with other digital data.
- DEMs allow automated disaggregation of the landscape into land units given derived explicit rules for recognition. Automation adds objectivity to this classification, allowing an objective solution to problems, quantitative comparisons and repeatability of results.
- The inherent relationship between surface topography and hydrogeological function, referred to above.

The fundamental feature which distinguishes HARSD is this reliance on a DEM as the basis of inferring groundwater behaviour and aquifer properties.

Constructing Hydraulic Head Surfaces with a DEM and Sparse Water Level Data

An alternative to inferring a hydraulic head surface (HHS) in the absence of observed water levels, often there are sparse water level data available for a particular groundwater system. Typically, they will be unevenly distributed across the domain as well as sparse, creating the potential for much artefact in the HSS's resulting from methods such as manual fitting, interpolation and kriging.

The HARSD approach identifies two alternative hydrogeological techniques incorporating GIS methods for generating hydraulic head surfaces. In the first technique, a least-squares regression, is derived between the reduced water levels and surface elevation, and the developed regressions are used in a GIS environment to prepare water level maps. These regressions may be developed globally or uniquely for each land unit. In the second technique, a land unit classification based on the hydrogeomorphic characteristics of the catchment is used to define the depth to water in each zone. Because regression relationships can be developed against a hydrogeomorphic classification, the two approaches are not mutually exclusive.

a) An example of regression relationships between elevation and water levels - the Upper Kent River catchment

Where the spatial distribution is more or less even across the domain, then a reasonable HHS can be developed on the basis of an empirical (least-squares) fit between surface elevation and groundwater levels, using either linear or higher-order regression techniques.

For the Kent catchment, vegetation cover was interpreted from SPOT satellite imagery. The whole domain was then divided into remnant vegetation and non-remnant vegetation areas. The reason for this was the generalised observation that recharge was negligible under remnant vegetation, and thus a different relationship between surface and groundwater elevations would exist. Data from bores located within remnant vegetation areas were used for regression analyses, with an equivalent but independent analysis performed using borehole data from within cleared areas.

Two nonlinear regressions were thus defined:

$$Pw = 128.05 \ln(Z) - 472.68 \quad \text{(remnant vegetation)}$$
$$Pw = 208.04 \ln(Z) - 904.66 \quad \text{(cleared areas)}$$

These regressions can be used in the GIS environment to construct the water level map for the entire domain.

b) Hydrogeomorphic classification of catchments

The HARSD approach is based on the disaggregation of the landscape into hydrogeomorphic units which may be expected to have similar aquifer properties and recharge/discharge behaviour. The design of hydrogeomorphic units is based on the idea that in addition to geological controls, topographic controls are also important in distributing the recharge potential. Hence, we maintain that the use of a classification procedure which takes both geology and topography into account is, *a priori*, better than using geology alone.

Similarly, the extrapolation of locally-measured aquifer parameters is an equivalent challenge. Argued on the basis of current theories about landscape evolution, hydrogeomorphic principles which relate geomorphological development (weathering and erosion) to topography and geology should lead to an improved expectation of how hydraulic properties, such as specific yield and transmissivity, are distributed across a landscape.

The first step in defining the spatial co-dependencies in aquifer parameters is to classify the catchment into landscape units which can be expected to operate uniquely. The theory states that the shape of a landscape is a function of climate and geology, resulting in slopes which together with geology control the movement of groundwater through their mutual influence on transmissivity and hydraulic gradient. The resulting (surface) aquifer system’s hydraulic head surface is largely a subdued (smoothed) reflection of topography. Hydrogeomorphological classification divides the landscape into areas with similar aquifer properties and thus hydraulic response; for each of these the relationship between land surface and groundwater level may be uniquely defined.

This classification process can proceed in a number of steps from morphological mapping (to include slope angle, profile curvature and landform elements), through geomorphological mapping (adding consideration of the origin of the landforms, past and present processes, together with the geological history) into hydrogeomorphological mapping. A hydrogeomorphic unit is defined as a group of morphological units which have similar weathering and erosion pattern, with hydrological and hydrogeological characteristics controlled by geomorphological processes. The process of deciding on which topographic properties offer the greatest insight into hydrogeological behaviour, and in turn which class ranges offer the best disaggregation of the domain into hydrogeomorphic units, is ultimately subjective. However, it is based on examination of the statistical distributions of surface properties and cross-sections which are sampled from the DEM by wholly objective, explicit and repeatable means. The application of the derived rules in mapping the land units thus defined is also objective and repeatable.

The purpose of a GIS-based approach for hydrogeomorphic mapping is to develop and then objectively apply geometrical and reproducible attributes and rules to the classification of a region into landforms. There are three principle steps involved in the process of automated terrain classification:

- Derivation of primary topographic attributes
- Statistical and graphical analyses of variables
- Classification of hydrogeomorphic units

These are given in some detail by Salama, Hatton and Dawes (1996).

Application of the HARSD technology in salinity studies

The HARSD technology provides among other information an identification of discharge and potential waterlogged areas. If a groundwater level map is available for a region, or if one has been prepared by the methods using the techniques mentioned above, then discharge areas can be predicted and mapped. In this prediction, the absolute elevation of the HHS is of critical importance, and the results will be extremely sensitive to systematic errors in the height of predicted water levels. This can be controlled for, to some extent, by using known, mapped discharge areas as controls on the selection of the morphometric criteria (as described above) to be applied across the domain.

In the general case of modelling land use or climate change impacts on groundwater discharge, e.g., in predicting the potential remediation of dryland salinisation, a basic strategy using HARSD-derived HHSs and the Flownet Software can be applied. The prescription in this case is as follows:

1. Derive a HHS for the catchment of interest, as described above.
2. Input the surface into the Flownet Software.
3. Within the Flownet Software, specify the spatial distribution of recharge under current land use and climate.
4. Specify transmissivities where known or where they can be estimated.
5. Generate the flow net. At this stage, the fluxes of groundwater can be derived at any point in the catchment. These fluxes can be compared with known groundwater discharges for more refined calibration.
6. To model land use or climate change, revise spatial recharge estimates so that they correspond to those expected under a different regime.

Recharge estimates to calibrate the flow-net analysis can be derived either by the association of inverse estimates from bore hydrographs or salt/isotope profiles with the hydrogeomorphic unit/land use/climatic zone combination within which the measurement took place, or through the application of a recharge model which takes these factors into account.

The software associated with flow net analyses is described by Dawes, Hatton and Salama (1996) in *User Manual for* FAS*: Flownet Analysis Software.*

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