JOURNAL OF HYDROLOGY (N.Z.) Vol. 10, No. 1, 1971

LOW FLOW CHARACTERISTICS ON THREE ROCK TYPES OF THE EAST COAST, AND THE TRANSLATION OF SOME REPRESENTATIVE BASIN DATA*

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ABSTRACT

Low flows on 13 limestone, 13 siltstone and 9 argillite basins of the East Coast, North Island, were measured at two- or three-day intervals during a dry period. For each rock type, low flows, and their recession coefficients (k) during a 16-day reference period, were related to various basin morphological features and to normal annual rainfall.

Recession coefficients differed significantly: for limestone basins mean k=0.975 (±0.017), for siltstone mean k=0.924 (±0.025), and for argillite basins k=0.905 (±0.041) – noting that the decrease of k is coupled with an increase in its variability. Some explanation of this variability within each basin rock group was sought by undertaking Pearson's correlation analyses between k and six basin features. On limestone the very small variability of k could not be simply explained; on siltstone the wider variability of k could not be simply explained by any basin feature used; but on argillite the best simple explanation of k was with main channel length/area, which explained 55%.

Simple correlations between flow, per unit area, at the start of the 16-day reference period (q_0) and basin features indicated that on limestone normal annual rainfall explains 96% of the variation in q_0, on siltstone rainfall explains 41% of q_0, while on argillite only 6% is thus accounted for. On argillite the best simple explanation of q_0 is basin area, which explains 62%.

Study results suggest the hypothesis that the higher is the basin k value, the more efficient is the long-term basin storage factor and hence the closer is the relation between long-term average storage input (normal annual rainfall) and ground-water flow (q_0) at any time during normal recession.

The translation of some data from Omakere and Otane representative basins to other basins on siltstone and limestone respectively is dealt with. Annual rainfall and water yield data from both representative basins correlate highly (r=0.98) and therefore afford a means, where rainfalls are well defined, of estimating annual water yield from siltstone and limestone basins.

Using Omakere data, the estimation of low flow and duration of zero flow for other siltstone basins is discussed.

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* Paper presented at IASH Symposium on Results of Research on Representative and Experimental Basins, Wellington, 1970.

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The lower portions of the flow duration curves for Omakere and Otane basins are presented; some of the basin processes apparently controlling the shape of the curves are referred to, and the translation of this knowledge to other basins for the synthesis of flow duration curves is broadly considered.

The influence of rock type on flow characteristics is important and there is a need within a climatic regime to recognize rock type rather than broad hydrological region.

The value of a representative basin for reliable data translation is proportional to the degree to which basin processes can be quantified and understood.

INTRODUCTION

The results of stream flow measurements during dry periods on the East Coast over a number of years have given rise to the postulate that in dry weather the rates of flow from different basins are related closely to major spatial differences of average annual rainfall amount, and also to basin geology. To test this, a study was designed involving basins on three distinct rock types in an area with the same climatic characteristics and where the rainfall station network was adequate. The results of this preliminary study are reported and discussed.

Further investigations, both on the same rock types and on others, are necessary. However, the present results appear to give a sufficient indication of the chief hydrological processes involved for their immediate use in the translation of representative basin flow characteristics to other basins. Accordingly, the translation of data determined during five years at two representative basins is also discussed.

STUDY AREA

The study area of about 5,200 km^2 (2,000 square miles) lies south of Napier (Fig. 1) and comprises all the Southern Hawke's Bay, the eastern portion of Napier, and a northern section of Wairarapa hydrological region (Toebes and Palmer, 1969). Omakere basin represents Southern Hawke's Bay region, and Otane basin represents Napier region.

Altitudes rise to around 610 m (2,000 ft) but by far the greater area lies below 305 m (1,000 ft). Land use is chiefly pastoral; forest and scrub occupy only a very small proportion of the area. Average annual rainfalls range from 760 mm (30 in.) to 2030 mm (80 in.). Orographic control of rainfall is strong, causing annual amounts to increase markedly with altitude, and therefore over very short distances. Variability of both annual and monthly rainfall is great (Seelye, 1940; 1946) and droughts are frequent

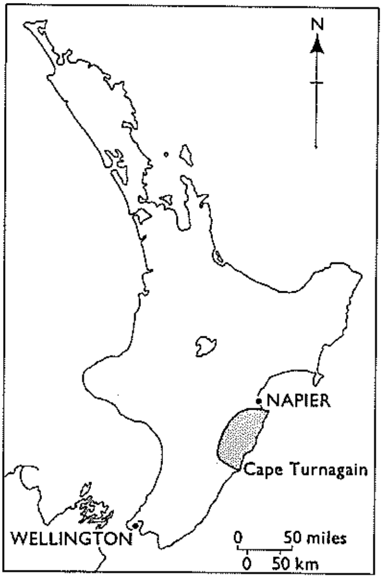

FIG. 1 — North Island, New Zealand, with the study area shown shaded.

(Grant, 1968). Drought duration averages 50–60 days where annual rainfalls are 760–1020 mm (30–40 in.), and it has attained 150 days.

Similarly stream flow, which is widely used for domestic and agricultural purposes, has great variability. During summer–autumn (December–May) all streams flow either very low or dry up. It has earlier been observed that flows from limestones frequently persist through severe droughts; on siltstones many streams fall to zero flow during a dry period, and on argillite many flows tended to cease very early in a dry period. Accordingly, study of dry-weather flows on limestone, siltstone and argillite which occur within the study area was planned.

The limestones are hard coquina formations – composed of shell detritus – of Pliocene age and are usually 150–450 m (500–1500 ft) thick (Kingma, 1962). The blocks are usually sharply tilted to produce a clear distinction between escarpment and back slopes.

The siltstones, of Pliocene-Miocene age, are pale to dark grey and often massive. Locally, calcareous siltstones grade laterally into alternating sequences with medium-grained sandstones and muddy siltstones. Hillslope instability is widespread, especially where the siltstones are muddy.

Argillites within the area are of Upper Cretaceous age; they are pale grey, hard and very shattered. In general they are slightly calcareous, and locally contain flint beds and large concretions.

STUDY METHODS

Initially, 17 basins with measuring sites were selected on each of the three rock types. During a dry autumn period, flows were measured at each site, either by current meter or by volumetric means, at two- or three-day intervals. For each basin, flow was plotted against time, and for a selected 16-day reference period a flow recession curve was drawn. Erratic results, probably due largely to problems of measurement of very small flows and to upstream extraction by pumping, reduced the reliable basin series to 13 on limestone, 13 on siltstone and 9 on argillite.

The major physical characteristics of each basin group derived from the inch-to-the-mile topographical maps (NZMS 1 series), are summarized in Table 1. Basin vegetation is predominantly pasture but a few basins have large areas of tall scrub and young forest which may be hydrologically important and these receive comment where pertinent.

Normal (1921–50) annual rainfall was determined for each basin from the rainfall station network. Rainfall ranges for each basin group are shown in Table 2, as also are value ranges of q_0 (flow rate at the start of the 16-day reference period) to give an idea of the magnitude of flows under consideration.

For each of the 35 study basins the recession coefficient, k, during the 16-day reference period was calculated using:

$$q_{16} = q_0 k^{16}$$

giving

$$\log k = \frac{\log q_{16} - \log q_0}{16}$$

where q_0 is the flow at the start of the period and q_{16} is the flow at the end of the period.

TABLE 1 — Basin physical characteristics on three rock types.

Basin feature	*Limestone*	*Siltstone*	*Argillite*
No. of basins	13	13	9
Mean area (km^2)	21.99	31.91	9.92
Mean length (km)	7.13	8.05	4.68
Altitude range (m)	23–550	15–490	18–550
Mean slope (m/m)	0.044	0.034	0.061
Mean channel slope (m/m)	0.036	0.025	0.051
Mean drainage density (km/km^2)	2.29	2.40	2.62

TABLE 2 — Basin rainfall and flow characteristics on three rock types.

Basin feature	*Limestone*	*Siltstone*	*Argillite*
Range of normal annual rainfall (mm)	890–2030	1020–1400	1140–1400
Range of q_0 ($\mathrm{l\ s^{-1}km^{-2}}$)	0.25–17.70	0.80–7.20	1.27–10.03
k values:			
mean	0.975	0.924	0.905
std dev.	0.017	0.025	0.041
maximum	0.991	0.957	0.959
minimum	0.944	0.878	0.822
max.–min.	0.047	0.079	0.137

STUDY RESULTS

For each study basin, values were determined for: (a) morphological parameters considered important; (b) normal annual rainfall as an index of long-term input; and (c) dry-weather output in terms of flow, q_0, and recession rate, k. The relations among these parameters were studied with the prime aim of explaining the measured variations of both q_0 and k in terms of variables that are independent of them. In doing this the introductory postulate was tested.

Ground Water Recession

There are significant differences of mean k value among the three rock types (Table 2). From limestone, through siltstone, to argillite the decrease of mean k is coupled with an increase in variability of k. Values indicate that in terms of long-period storage, limestone is the most efficient and argillite the least efficient. For limestone basins it is worth noting that the two lowest k values (0.944, 0.959) are for the only two basins lying on the steep escarpment slopes. For the 11 limestone basins on back slopes, mean k is 0.980 with one standard deviation being 0.010.

The three rock-type basin groups are neither physically comparable (refer Table 1) nor are they necessarily representative samples of the three populations. Nevertheless, the pattern of k-value differences (Table 2) is sufficiently distinctive to be immediately useful. But further to this, some explanation of variation of k values within each basin group is required; it was considered that explanation was to be found in terms of basin morphology. Therefore, for each rock-type set of data simple correlations were determined between k and five basin morphological features. Relations between k and normal annual rainfall were also defined. The results are shown by the tabulations of Pearson's r values in Table 3.

It is outstanding that significant values of r were obtained only for argillite basins – the basin set having the lowest mean k value and the greatest variability of k. The best simple explana- of k on argillite was found with main channel length/area where for $r=0.74$ the explanation of k is 55%. It should be recorded that the two highest k values on argillite (0.959, 0.951) were for the only two basins containing at their head a large area of tall scrub and regenerating forest.

No satisfactory simple explanation of the variation of k was found for either limestone or siltstone basins. But, of course, for limestone basins the average variation of k was very small, being only ±0.017 for 68% of all 13 basins, or ±0.010 for 68% of the 11 back-slope basins. Degree of channel entrenchment must influence ground water flow, and especially on siltstone basins it may be an important parameter; but for this study it has not been assessed.

An interesting feature of the pattern of r values in Table 3 is that for every basin feature there is a distinct trend in the values from limestone, through siltstone, to argillite. In four cases the trend towards argillite is negative; in two it is positive.

Dry Weather Flows

Simple correlations were undertaken between the flow at the start of the study reference period (q_0) and basin features, including rainfall. To overcome differences of basin area all flows were converted to a unit area, and they are subsequently expressed as litres per second per square kilometre ($l\,s^{-1}\,km^{-2}$). Table 4 presents the results.

On limestone, normal annual rainfall explains 96% of the variation in q_0. On siltstone, rainfall explains 41% of variation in q_0, while on argillite only 6% is thus accounted for. On siltstone other features do not usefully increase the explanation of q_0 variation, but on argillite the best simple explanation is basin area, which explains 62%.

TABLE 3 — Relations between k and different basin features on three rock types, expressed as Pearson's r values.

Basin feature	*Limestone*	*Siltstone*	*Argillite*
Area	0.27	– 0.24	– 0.60**
Channel slope	– 0.35	– 0.18	0.53*
Main channel length	0.22	– 0.06	– 0.59*
Main channel length/area	0.00	0.19	0.74***
Drainage density	0.23	0.07	– 0.12
Normal annual rainfall	0.22	0.17	– 0.47

Significance levels: 0.1% ****; 1.0% ***; 5.0% **; 10% *.

TABLE 4 — Relations between q_0 and different features on three rock types, expressed as Pearson's r values.

Basin feature	*Limestone*	*Siltstone*	*Argillite*
Normal annual rainfall	0.98****	0.64***	0.25
Area	0.82****	-0.05	0.79***
Channel slope	-0.51**	-0.06	-0.52*
Main channel length	0.67***	-0.06	0.74***
Main channel length/area	-0.51**	0.22	-0.76***
Drainage density	-0.47*	0.00	0.31
Flow feature:			
k	0.28	0.02	-0.78***

It is noticeable that, on limestone, basin area ranks second to rainfall in explaining q_0. On siltstones the failure of area, and some other basin features, to correlate significantly with q_0 may indicate that some unrecognized major differences exist in the processes controlling low flow. It could be, as suggested in relation to the variability of k, that degree of channel entrenchment is an important controlling factor on siltstone.

HYPOTHESES AND PREDICTION

From limestone, through siltstone, to argillite both the trend of k values and their variability (Table 2), and the trend of correlation coefficients relating q_0 to rainfall (Table 4) support the hypothesis: *within the same climatic region the efficiency of basin short-term storage of rainfall input, as indicated by the* k *value, largely determines the efficiency of long-term storage of input.* In other words, the higher is the basin k value the more efficient is the long-term basin storage factor and hence the closer is the relation between long-term average storage input (normal annual rainfall) and ground water flow (q_0) at any time during normal recession.

The relation between k and the dependence of q_0 on rainfall must alter in different climatic regimes. That for the study area is defined in Fig. 2, which although based on basin group mean values, could reasonably be applied to individual basins.

Fig. 3 presents the quantitative relations between low flow, q_0, and normal annual rainfall for limestone and siltstone basins — the relation was not significant for argillite basins (Table 4). Figs. 2 and 3 may be used in combination for broad predictions of unknown parameters on ungauged basins. For example, on either a limestone or siltstone ungauged basin for which only rainfall is known, a useful first estimate of low-flow characteristics, with approximate limits of accuracy, may be made in terms of the

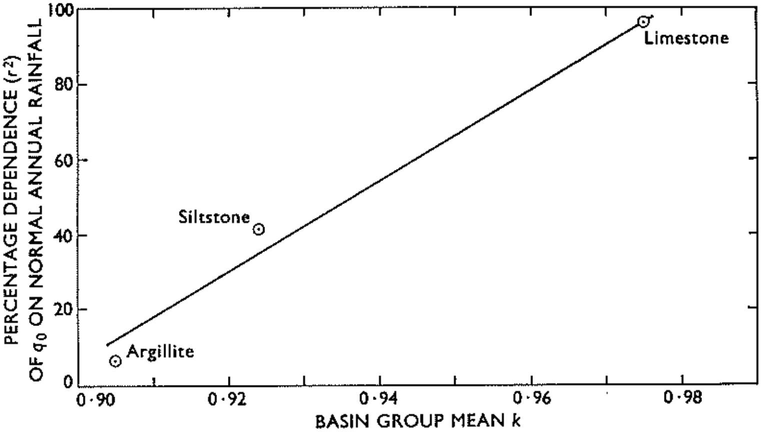

FIG. 2 — Relations between basin group mean k values and the percentage dependence of q_0 on normal annual rainfall.

quantitative data of this study. On the other hand, with a knowledge of low-flow characteristics for, say, a limestone basin in an area lacking reliable rainfall records, a close estimate of the basin normal annual rainfall is possible.

Use of the present study data for such predictions and estimates would usually require some quantitative adjustments, and for this at least one of the study basins would be used as a reference – the most suitable for each rock type being the pertinent representative basin in the area.

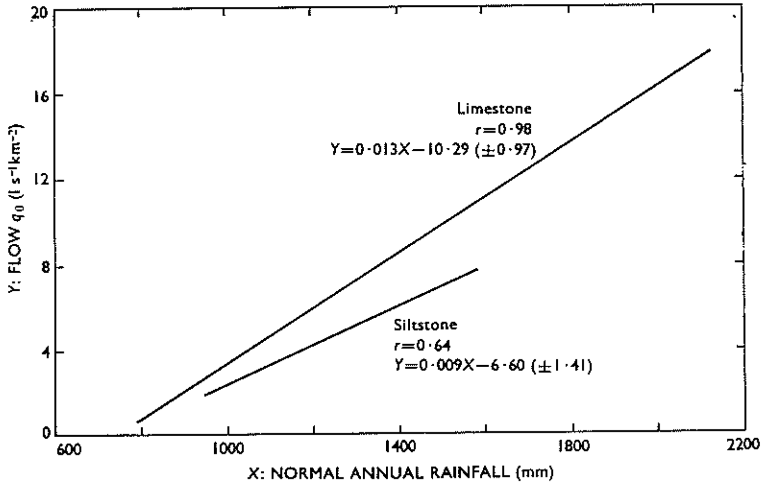

FIG. 3 — Relations between flow and normal annual rainfall on limestone and siltstone basins.

It is postulated that limestone basins on escarpment slopes have significantly lower k values than basins on back slopes. Further investigation is necessary, but in the meantime the difference should be recognized for prediction purposes.

For ungauged argillite basins, main channel length/area may be a useful parameter for the estimation of k ($r^2 = 55\%$, Table 3) but further investigations are required on a larger number of basins.

REPRESENTATIVE BASIN DATA TRANSLATION

Otane basin at Glendon is the representative basin for Napier hydrological region. Its area of 23.8 km² is composed of 49% limestone, 35% argillite and 16% argillite gravels. This geological complexity has obvious disadvantages but they do not seriously reduce the value of the basin for the translation of data to limestone basins because Otane has the essential low-flow characteristic of limestone basins in that it rarely runs dry. Otane was included in the limestone study basins.

Omakere basin at Fordale, of 54.4 km², is situated entirely on siltstone and it was included in those study basins. It is the representative basin for Southern Hawke's Bay region.

Rainfall and flow data are used, for Otane for the years 1965–68, and for Omakere for 1964–68.

Annual Flows

Because Otane and Omakere basins are under the same climatic regime – they are only 24 km (15 miles) apart – their annual rainfall and water yield data have been combined to produce nine pairs of values. The two parameters correlate highly ($r = 0.98$, $P = 0.001$) and the relation is shown by Fig. 4. The regression equation indicates that for 68% of estimates of water yield the error at the 1500-mm (60-in.) rainfall level is about 6%, and at the 1000-mm (40-in.) level it is about 17%. In the study area, where rainfalls are reasonably well defined, the relation (Fig. 4) is therefore useful for estimation of annual water yield from limestone and siltstone basins.

It follows that the same relation may be used, within the defined range, to estimate annual water yields for different recurrence intervals based directly on the return period of annual rainfall amounts.

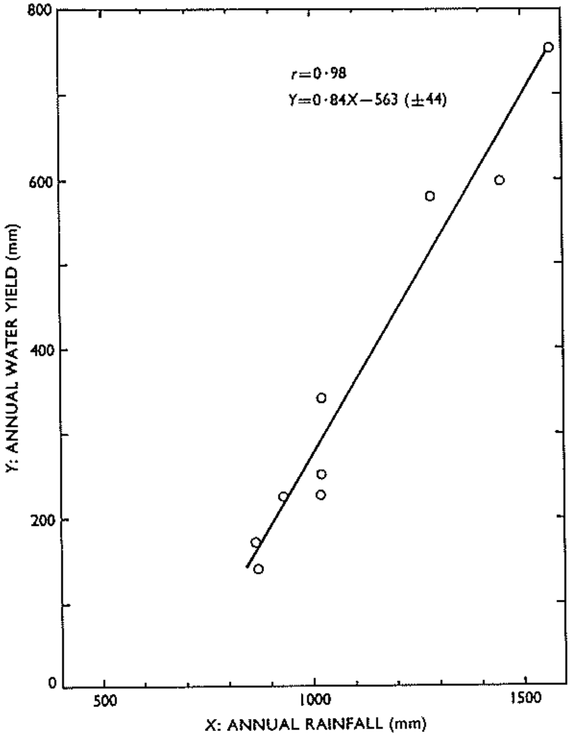

FIG. 4 — Annual water yield and rainfall relations for Otane and Omakere representative basins.

Low Flows

For the 16-day study reference period, flows from Omakere representative basin were plotted against corresponding flows from six of the other study basins on siltstone (Fig. 5). Omakere flow at Fordale was zero for 158 days in 1964, for 32 days in 1965 and for 55 days in 1968. The approximate durations of zero flow may be determined for each of the six basins from the relation of each to Omakere. The indications (Fig. 5) are that Trig 35, Mangarouhi, Tamumu and Ponui basins, in that order of drying up, will attain zero flow before Omakere at Fordale, while Purimu and Makara basins will cease flowing after Omakere. For the period 1964–68, zero flow from Omakere occupied 13.4% of the time; although this reference period is very short, it does give a good start for the prediction of average zero flow duration on other siltstone basins.

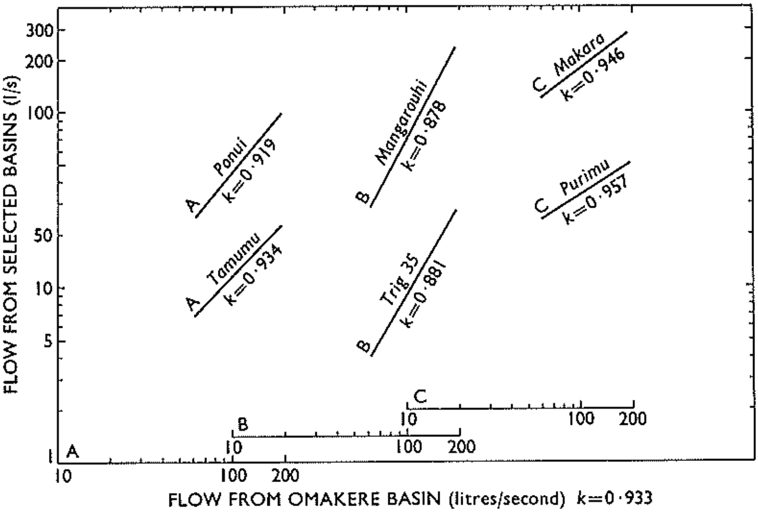

FIG. 5 — Low flows, during the 16-day study reference period, from selected siltstone basins compared with flows from Omakere representative basin.

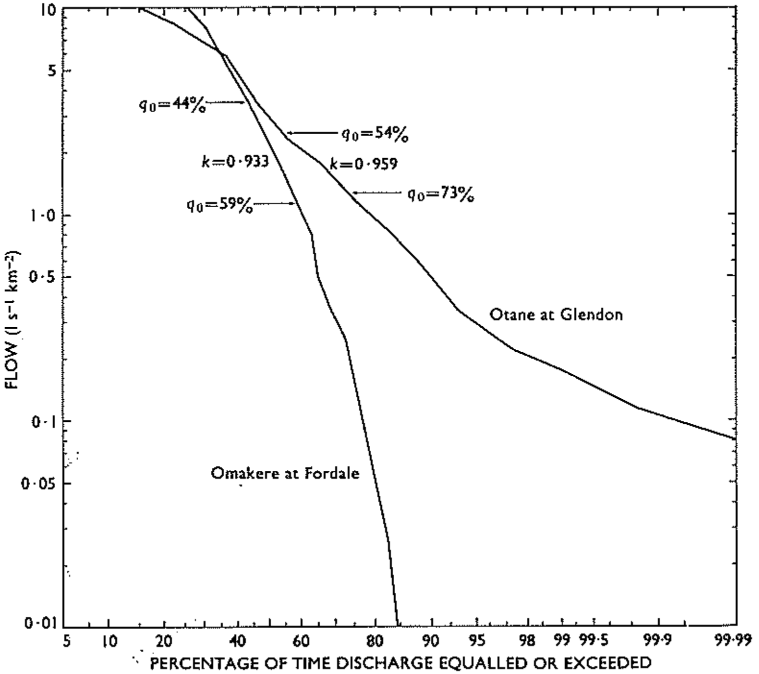

FIG. 6 — Portions of the flow duration curves for Omakere and Otane basins, showing the respective sections embraced by the 16-day study period.

Fig. 6 shows the lower portion of the flow duration curves for Omakere at Fordale (1964–68) and for Otane at Glendon (1965–68). For direct comparisons flow is expressed per unit area (km^2). On each curve is marked the flow range embraced by the 16-day study period. For Omakere this is the duration range 44–59 percentage of time discharge was equalled or exceeded, and broadly this 15% range could be transferred to the 16-day study period flows for all siltstone basins (see Fig. 5). But this direct translation is strictly true only for basins with k values the same, or very nearly the same, as that of Omakere. Where k values are higher than that of Omakere (>0.933) the flow duration range represented must be larger than 15%; conversely where k values are <0.933 the duration range represented must be smaller than 15%. In either event there is not likely to be a coincidence with Omakere for either the upper or lower duration percentage value, but the displacement, or estimation error, is not likely to jeopardize the practical value of early predictions made by this method of translation.

For Otane the 16-day study period embraces the flow duration percentage range 54–73, and for translation to other limestone basins the above comments apply. However, more accurate translation is possible for most limestone basins because of the small standard deviation (0.017) of the k values.

On Fig. 6 we may note the slope change of the Otane curve about 0.3 $\mathrm{l\,s^{-1}\,km^{-2}}$ which indicates that at smaller flows the k value increases. It is highly likely that about the stated flow value the argillite in the basin ceases to yield ground water, leaving only the yield from limestone which has higher k values. The geological complexity of Otane – a feature common to numerous basins in the region – is a disadvantage, but for reliable data translation it is simply necessary to quantify and understand the processes occurring in the reference basin.

The Omakere curve (Fig. 6) shows progressive slope steepening indicative of reducing k values. This may be realistic, but it could result from channel evaporation losses.

Further work is required for satisfactory quantitative explanations of low-flow processes in both Omakere and Otane representative basins so that translation of data to other basins on siltstone and limestone respectively can be reliably achieved for minimum time and effort.

Below 6.0 l s^{-1} km^{-2} (Fig. 6) yields from Omakere are considerably lower – even allowing for possible evaporation losses – than those from Otane notwithstanding that Omakere basin normal annual rainfall is 1295 mm and for Otane it is 940 mm. This large difference of low-flow pattern can be attributed, in the main, to the rock type difference.

FURTHER COMMENTS

Flow Duration

For limestone and siltstone basins, annual water yield can be assessed (Fig. 4), and a reasonable estimate made of the lower half of the flow duration curve from reference station data – as discussed above. Now, the area under the full annual duration curve represents the annual water yield, and of this the lower half can be determined. It follows that the approximate area under the upper half can be derived. This leaves only the shape of the upper curve to be defined, and this is largely a function of rainfall amount and intensity, and basin morphology. Rainfall amount in the study area is positively related to the frequency of the larger daily rains (Grant, 1968), which produce the larger flows that determine the form of the upper duration curve. Future analyses of high flows on the representative basins should supply necessary information on relations and make it possible to translate reliably the full flow duration curve of a representative basin to any other basin on the same rock type.

Basin Representativeness

Representativeness does not require of a basin that it possesses the average flow characteristics for a region, or that it be of average area, slope, etc. Omakere basin runs dry – not all siltstone basins of the East Coast run dry. But from Omakere the low-flow characteristics of other siltstone basins can be determined.

Many hydrological regions in New Zealand are geologically heterogeneous; this is particularly true of the East Coast of the North Island. The present study has highlighted the important influence of rock type on flow characteristics and the results point to the need for the recognition, within any one climatic regime, of rock type rather than broad hydrological region. Present knowledge suggests that for low-flow data translation to any limestone basin on the East Coast, irrespective of the hydrological region as mapped, Otane is the best reference basin.

The value of a representative basin for reliable data translation is proportional to the degree to which basin processes can be quantified and understood.

General

When analysing the relations of Tables 3 and 4, it was known that many basin features correlate highly among themselves, but this is unimportant because, at this stage, the best simple relations were aimed at for the estimation of k and q_0. Multiple correlations will be tested in future work.

ACKNOWLEDGMENTS

This study helps to fulfil one of the aims of a major research project on surface water resources of the East Coast. It is based on field measurements and analyses carried out by Napier Hydrological Survey staff of the Ministry of Works whose co-operation and assistance is gratefully acknowledged.

Permission to present and publish this paper was given by the Commissioner of Works.

REFERENCES

Grant, P. J. 1968: Variations of rainfall frequency in relation to drought on the East Coast. *Journal of Hydrology (N.Z.) 7* (2) : 124–135.

Kingma, J. T. 1962: Sheet 11, Dannevirke (1st ed.). *Geological map of New Zealand.* 1:250,000. Department of Scientific and Industrial Research, Wellington.

Seelye, C. J. 1940: Variability of annual rainfall in New Zealand. *N.Z. Journal of Science and Technology 22B* (1) : 18–21.

Seelye, C. J. 1946: Variations of monthly rainfall in New Zealand. *N.Z. Journal of Science and Technology 27B* (5) : 397–405.

Toebes, C.; Palmer, B. R. 1969: *Hydrological regions of New Zealand.* Miscellaneous Hydrological Publication No. 4. Ministry of Works, Wellington. 45 p.