INFILTRATION IN THE PUKETURUA EXPERIMENTAL BASIN

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ABSTRACT

During the three years 1965–67, the North Fork infiltrometer has been used extensively in the Puketurua Experimental Basin, Northland, to examine the infiltration characteristics of the soil units present. This paper evaluates the field technique and presents an account of efforts to improve the instrument, together with an outline of a new computer programme for the processing of sprinkling-plot data, and an analysis of the data obtained.

INTRODUCTION

Infiltration, simply expressed as the flow of water into the soil, is an obvious characteristic for measurement in any experimental basin. Numerous instruments have been used to measure infiltration rates and capacities (UNESCO, in press), but none has proved entirely satisfactory. Reliable data are difficult to obtain because of the complexity of the climate-water-soil-plant relationship.

Throughout New Zealand the North Fork infiltrometer‡ has been used to obtain infiltration data on a number of soil units (Nordbye and Campbell, 1951). It was introduced in 1964 by the Ministry of Works to the research programme of the then newly established Puketurua Experimental Basin, Northland, to obtain:

(i) infiltration data for the soil units present, and
(ii) mean infiltration data for the three catchments in the basin.

Infiltration data are required for all phases of the land-management programme, which involves a change from the current scrub cover to introduced grasses, later modified by conservation practices.

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‡ Use of the North Fork infiltrometer is part of the programme of the Ministry of Works to determine infiltration rates of typical soil-vegetation complexes in New Zealand. Other methods of determination are being explored also. — Ed.

The second part of the experiment has not yet been started, as this depended on first obtaining satisfactory results for the soil units. The reasons why these were not obtained are dealt with in this paper. An account of efforts to improve the performance of the instrument, an outline of a new computer programme for the processing of sprinkling-plot data, and an analysis of the data obtained are followed by suggestions for further research.

DATA COLLECTION

Pilot studies (Campbell, 1945; Nordbye and Campbell, 1951) did not solve all the problems involved in working the infiltrometer. The main concern was the lack of consistent results from a given soil unit, also noted previously by Musgrave (1955). Differences between individual plots within a master site can be accounted for partly by micro-variations in the condition of the surface profiles. However, when repeat runs on the same plot produced inconsistent results, doubt was placed in the performance of the instrument — particularly since these results followed inexplicable data from some interplot runs.

Briefly, the equipment is of the rainfall-simulator type consisting of a set of sprinklers applying a known intensity of artificial precipitation to a rectangular plot (30 inches $\times$ 12 inches). Sprinklers situated at the lower end of the plot traject precipitation on to the plot; surface flow is collected in a tank where the water level is read with a manual vernier gauge. The difference between the volumes of precipitation and flow is the volume of water infiltrated (Rowe, 1940).

A systematic examination of the equipment was begun, the Ajax diaphragm valve being the first item investigated. This valve, used for adjusting the intensity of precipitation (Glass, 1965), was deleted from the system and the water head adjusted to produce an intensity of 3 inches/hour. Differences of 0.44 inch/hour still occured; this is well beyond the American maximum permissible deviation of 0.08 inch/hour. Pressure fluctuations in the water supply line were then checked by employing a constant-head tank in the system. Marked fluctuations were still present and it was thought that these could be the result of alternate bright sunlight and cloud conditions. During days of continuous sunlight or cloud the differences were much less. Before commencing operations it is very important to bleed the system in order to remove trapped air and to ensure adequate mixing of water in the leads. A pre-wetting run, using plot cover, for five to ten minutes prior to calibration, accommodates bleeding requirements and moistens the area surrounding the plot.

More recent investigations connected with alpine interception research, in which automatic recording equipment was employed and the infiltrometer was used to spray selected vegetation samples, showed little variation during a run, even under changing weather conditions. Valves are now available which will ensure a constant rate of application. Other problems, also largely solved, are: the lack of a low intensity more typical of natural precipitation conditions; uneven distribution of artificial precipitation; the inaccuracy of the vernier gauge in the run-off collecting tank. The recent use of overhead nozzles has enabled a reduction of the precipitation intensity to 0.50 inch/hour, as well as ensuring an even spread over the plot, and with further testing an even greater reduction could be made. Run-off can now be more accurately recorded by a strip-chart recorder with a chart speed of 0.1 inch/minute. Further work is still required to obtain correct droplet size, although the range is now from fog to large drops.

DATA PROCESSING

In an effort to account for causes of variation (other than instrument errors) in the Puketurua data, a computer programme was prepared. This was intended to eliminate problems in the present method of sprinkling-plot infiltration analysis (Toebes, 1963). Manual processing of data is lengthy and subjective, requiring the work of skilled analysts to minimize error. This programme (Water and Soil S.C. No. 65), written in Algol for the Elliot 503 computer, ensures rapid and accurate handling of field data.

The sprinkling-plot programme is designed to process data obtained from a plot which has been sprayed with artificial rain at a predetermined intensity. The programme output starts with the heading, containing a record of plot details and the date of the run, followed by a tabulation of soil-moisture means. The precipitation rate should be constant throughout a run — current practice is to make calibration runs before and after the experiment, rejecting the calibration if the results of these runs differ by more than a predetermined limit. The programme, in accepting runs, assumes a linear relationship between the precipitation rate and time, whereas manual methods used an average constant rate throughout the experiment which assumes a random variation (of which the two calibration figures are a part) about the mean. Calibration runs represent an average for five minutes before (and after) the run, which may last 30 minutes. Rates applied at the beginning of the run are thus more likely to be near the initial calibration rate than the final one, making a linear relation a better first approximation to the true relation than a mean value. This was confirmed by the improvement in results obtained from runs with widely differing calibrations.

The method used for the calibration of infiltration values is similar to that outlined by Toebes (1963). A surface detention relationship is calculated by fitting $D_a = aq_o^n$ (a and n constants) by linear regression, after making suitable logarithmic transformation of surface-detention and overland-flow estimates following the cessation of precipitation. Assuming this relation is identical when run-off is increasing, it is used to calculate and tabulate mass-infiltration figures at the same time as overland flow is measured using

$$F = P - Q_o - D_a.$$

The equation of Horton (1939) is

$$f_c = f_{ult} + (f_o - f_{ult})e^{-kt},$$

and therefore, using

$$F(t) = \int_o^t f(t)dt,$$

$$F(t) = f_c \, . \, t + \frac{f_o - f_c}{k}(1 - e^{-kt}) \quad . \; . \; . \; . \; . \; . \quad (1)$$

Equation (1) is of the form

$$F(t) = b + ct - ce^{-kt} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

and is fitted to the results using the least-squares method of linear regression by means of the following procedure.

During the last five minutes of the run (assuming the run has been continued until the run-off rate is constant) the exponential term is negligible. Hence

$$F(t) = b + ct,$$

enabling b and c to be estimated using the results for this time interval.

To estimate k, equation (2) is rearranged to give

$$\log \frac{F(t) - b - ct}{-c} = -kt.$$

Linear regression analysis is applied to the remainder of the results, neglecting any for which

$$F(t) > b + ct$$

since, as can be readily verified, this results in a better approximation to the true curve than when the modulus of the expression

$$\frac{F(t) - b - ct}{-c}$$

is taken for all pairs of results.

Further work, similar to that done by Betson (1963), will develop the use of non-linear least squares to fit equation (1) directly to the results.

DATA ANALYSIS

The data from Puketurua, which amounts to approximately 100 runs, shows a large variation in the ultimate infiltration capacity for a given soil type. As has already been stated, this was caused partly by unreliable equipment. To complete the review, however, the data was assessed in relation to the physical condition of the infiltration plots. Six master sites, three in Waikare brown sandy clay (M/S 4, 5 and 6; 32 percent of the basin area) and three in Waikare clay and silt loam (M/S 21, 22 and 23; 57.5 percent of the basin area), were used in the investigations. Selected according to I.H.D. specifications, all possessed fairly uniform slope, aspect, soil and vegetation characteristics within their boundaries. Infiltration plots were worked from the bottom left-hand corner upslope in order to avoid unnecessary master-site damage.

The Waikare brown sandy clay located on slopes of 9–23° is strongly weathered, leached, and weakly podsolized. An A_1 horizon of dark friable humus may be present, overlying an A horizon of 2–4 inches of dark grey to dark yellow-brown heavy sandy clay, sometimes fine and structureless. Although the boundary between the A and B horizons is often blurred, the latter comprises 14–16 inches of fine, sandy clay loam, mottled with worm casts, and a strongly developed, coarse blocky to prismatic structure.

The brown clay master sites studied all have well developed profiles, although M/S 6 contains a higher percentage of sand and M/S 21 and 23 are complete but show the effect of sheet erosion, while most of the A horizon has been removed from M/S 22.

The antecedent median soil moisture prior to the majority of runs was between 30 and 40 percent. The dominant vegetation cover on all sites (*Leptospermum scoparium* and *Hakea acicularis*) was trimmed generally to one inch above ground level and most stubble removed. This eliminated interception.

A sample of infiltration capacities and precipitation intensities for each site is given in Table 1, while Fig. 1 shows a typical scattergram of the dependence of infiltration capacity on soil moisture and precipitation intensity. Although there is little dependence of f_{ult} on precipitation intensity, there is an apparent relationship between M_s and f_{ult} which is contrary to the concept of ultimate infiltration capacity (i.e. as the antecedent soil moisture increases, f_{ult} decreases).

TABLE 1 — A selection of infiltration data.

M/S	*No. of runs*	*Range f_c (in./hr)*	*Mean f_c (in./hr)*	*Range i (in./hr)*	*Mean i (in./hr)*
4	13	0.54–2.40	1.60	2.08–4.04	3.31
5	6	0.16–1.98	1.28	3.92–5.00	4.27
6	9	0.24–1.78	0.96	2.76–4.02	3.44
21	9	0.31–3.84	1.43	2.92–3.82	3.39
22	4	2.05–4.27	2.90	2.27–3.64	3.15
23	5	0.77–2.65	1.79	2.57–5.46	3.95

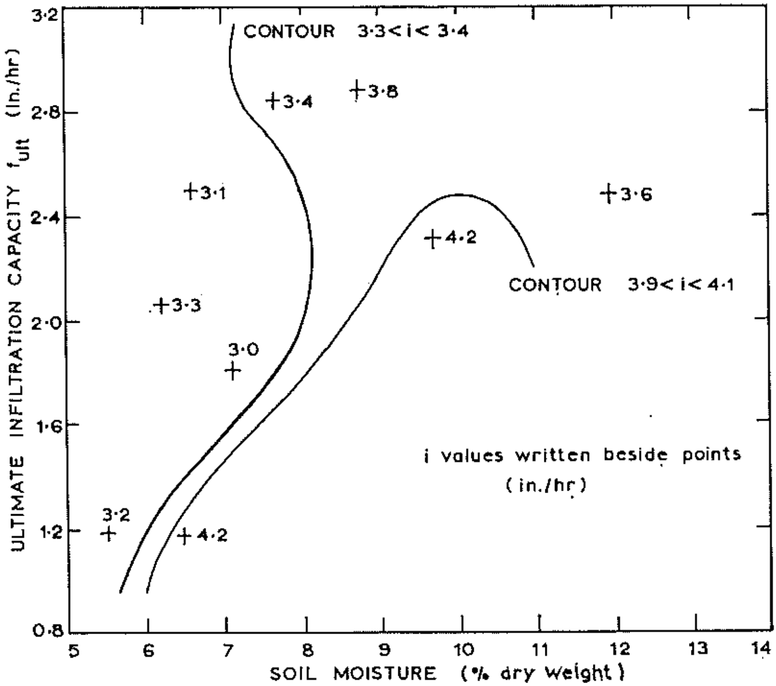

Fig. 1 — Comparison of ultimate infiltration capacity measurements, obtained with a North Fork infiltrometer, and antecedent soil moisture on M/S 22.

The runs on a given master site had been spread over a considerable period of time, hence a further set of runs was made on M/S 4 in three days. As Fig. 2 shows, these results are less scattered and f_{ult} is practically independent of M_s. This confirms that antecedent soil moisture is not indicative of ultimate infiltration capacity, this being a complex function of soil properties. These properties may vary with changing climatic conditions and explain the difference between the average of 4.2 inches/hour measured in May 1967 and that of 1.6 inches/hour measured in November 1965.

The results for this set of runs were calculated on the computer. Although the estimates of f_0 and k were too scattered for detailed analysis, the correlation coefficients calculated during each step of the curve-fitting process were, for runs whose calibrations differed by less than five percent of the average precipitation intensity, greater than 0.9. This indicated that within the limits of accuracy of the present data Horton's equation adequately describes the history of infiltration capacity for a run. This also suggested that the infiltrometer was operating correctly once assembled; the scatter in the results was therefore attributable to changes in the operating conditions of the instrument when moved and to dissimilar surface characteristics of the plots on a master site.

A smaller and more portable instrument would overcome the major disadvantages of the present infiltrometer by providing more samples in a given time interval, thus enabling more detailed examination of a smaller plot.

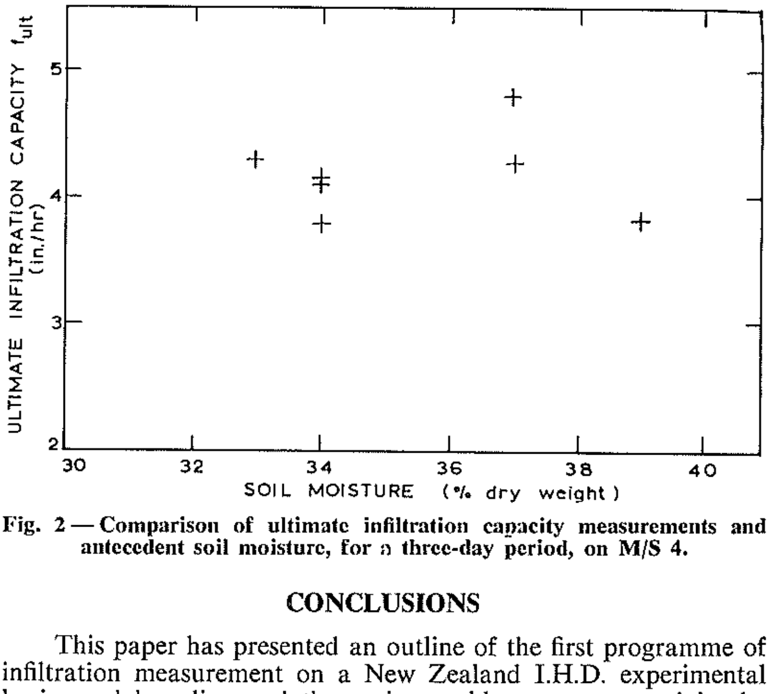

Fig. 2 — Comparison of ultimate infiltration capacity measurements and antecedent soil moisture, for a three-day period, on M/S 4.

CONCLUSIONS

This paper has presented an outline of the first programme of infiltration measurement on a New Zealand I.H.D. experimental basin, and has discussed the major problems encountered in the initial work.

The North Fork infiltrometer, in its basic form, appears to be of little value as an infiltrometer for the I.H.D. experimental basin programme. The Puketurua modifications were essentially a 'streamlining' of the original model. When working efficiently, it should be used to measure only infiltration capacities which may have some relative use — provided that the extent of variation shown in Fig. 1 is acceptable.

The following recommended modifications, made during the alpine interception programme, effectively rebuild the infiltrometer:

(i) The precipitation must be from an overhead nozzle (or nozzles) large enough to ensure a minimum application rate of at least 0.50 inch/hour. The droplet size can be reduced to that of a fog by using air-atomizing nozzles. This may introduce errors, but a small droplet size is a lesser problem than the customary minimum application rate of 2.5 inches/hour trajected on to the plot.

(ii) A run-off collecting tank which has an area ratio with the plot of 1 : 12 rather than the standard 1 : 3.

(iii) An automatic water-level recorder with a minimum chart speed of 0.1 inch/minute to replace the manual vernier gauge in the flow tank.

It should be noted that these changes do not shorten the costly field procedure, and it is therefore not recommended that the modifications be put into widespread use. Their value is in specialized work where a steady artificial precipitation is required. Future general field requirements could be met with the USGS Micro-rainulator infiltrometer (McQueen, 1963) which is more efficient, less costly, and ensures many more samples.

Improvements in the mechanical aspects of measurements have little purpose unless the characteristics of the plot surface and soil profile are surveyed in greater detail than was the case at Puketurua. A litter-filled fracture across one plot and not the other could cause an extremely high infiltration capacity in a soil which is normally impervious. Numerous hollows and twigs on the surface will increase depression storage and surface detention.

Use of the computer has greatly facilitated studies of the infiltration process — possibly the most complex process in hydrology — and this now allows the design of more elaborate field techniques than in the past. One useful approach will be the more accurate determination of k values for individual plots. It will be necessary to develop some new techniques for this purpose.

NOTATION

f	infiltration rate
f_c	infiltration capacity
f_o	initial infiltration capacity
f_{ult}	ultimate infiltration capacity
i	precipitation intensity
q_o	overland flow rate
F	mass infiltration
Q_o	mass overland flow
P	mass precipitation
D_a	surface detention
t	time
e	exponential function
k	decay constant
M_s	soil moisture
M/S	master site
a, b, c, n	constants

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