COMMENTS

Water under the bridge.

Comments on Farrington and Bellwood's 'Prehistoric Irrigation Hydrology of Pondfield Taro'.

M. J. T. Spriggs* and M. E. Sullivan**

* Australian National University, Canberra.

** National Parks & Wildlife Service, Sydney.

Although Farrington and Bellwood (1980) claim to take a novel approach, theirs was not the first application of the principles of open channel hydraulics to the study of taro irrigation systems in the Pacific. As long ago as 1927/28, the Annual Report of the Territory of Papua (now part of Papua New Guinea) gave details of the engineering features of the main canal at Wamira in Goodenough Bay, Milne Bay District (now Province). The account is worth quoting in detail:

> The engineering features of the scheme are: (a) A rubble dam, three feet high, constructed across the Uruam Creek at a point some miles above its mouth, Bartle Bay. (b) Main race, 1.5 miles in length. (c) Timber aqueduct at 1 mile 13 chains, conveying water across Davudavu Creek Gorge (aqueduct is 86 feet long and is elevated 30 feet above creek bed). (d) Distributary channels totalling 6 miles in length and serving 960 acres of rich black flat and smaller portion of land 40 acres in extent.
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> The existing main race has been graded evenly to a fall of 30 feet per mile, which appears to be the correct rate of grade for 'critical velocity' in this class of soil and with the present heavy growth of grass in the channel bed.
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> Under normal conditions, the capacity of this channel is about six cubic feet per second, but if kept clear of weeds and other marine growth, the rate of flow would be increased to ten cubic feet per second (1927/28:17).

The difference made to channel capacity by 'weeds and other marine growth' meant that flow was reduced to 60% of that in an unvegetated channel. Archaeological investigations relying upon excavated channel cross-sections and not taking account of factors such as channel vegetation may therefore seriously overestimate the rate of channel flow. An overestimate of 67%, the difference recorded between flows in a vegetated and unvegetated channel is serious indeed.

Similarly it is not accurate to describe one of the author's (Spriggs) own calculations from an operating taro pondfield system (quoted by Farrington and Bellwood, *ibid*:126) as 'using the techniques outlined in this paper' (an error which apparently crept in at the editorial stage). Spriggs' calculations were derived from measuring water velocity at the end of a vegetated irrigation channel, and therefore record the *actual* amount of water entering the pondfield system.[1] Such results obtained from working irrigation sytems are *not* directly comparable with those obtained by calculating velocity using the Manning equation with measured cross-sections of abandoned channels, unless adequate account can be taken of the extent of vegetation lining such canals when in use. Farrington and Bellwood do not take account of this critical factor when calculating coefficients of surface roughness (n) for either the Halawa Valley, Molokai or the Avana Valley Rarotonga.

Whether or not the channels were regularly cleaned, and how effectively, cannot readily be established archaeologically. Earle (1978:71) reports that present Hawaiian practice is to clean the canals twice yearly, and Spriggs's enquiries at Col de la Pirogue, New Caledonia, suggest that five times a year is necessary in some circumstances.

For the Wamira system the vegetated flow ($0.17m^3/sec$) is only 12.9% of the Hawaiian Legal Requirement (HLR) while the flow if the canal were kept clear of vegetation ($0.28m^3/sec$) would be 21.6% of the HLR. Kahn (1979:5) noted that in the Wamira area irrigated gardens are used only once, then abandoned for extended periods. Thus over five years, 65% of the total area could have been fed from the vegetated channel. During the same period if the channel had been rigorously cleaned, all of the garden area could have been used. To ensure an adequate fallow period to allow soil fertility to be replenished however, there would be no need to have continually cleaned the canal, and the flow in the vegetated channel as recorded would therefore appear to have been optimal for the system.

Using the Avana Valley, Rarotonga as an example, errors which can result from not taking account of channel vegetation can be examined. If we follow Farrington and Bellwood (*ibid*:125) in assuming that the Avana Valley channels operated at depths of 1, 2, 3 or 5 cm, then a more appropriate formula for mean channel velocity, V, (Leopold, Wolman and Miller 1964:157-8) in a relatively wide shallow channel would be:

$$V = \frac{1}{n} d^{2/3} s^{1/2}$$

and discharge (Q) can be calculated from Q=WdV, where W is channel width and d the depth of flowing water. The minor difference in result from applying either formula however is unimportant as

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[1] Spriggs used a standard technique suggested to him by Mr M. Fleming, a hydrologist at CSIRO. The time it took for a wine cork dropped into the canal to travel 10 metres (without touching the bank) was measured 20 times and then averaged. Velocity equivalent to that derived from a Manning equation calculation was taken to represent 80% of surface velocity.

regardless of which is used, application of the Manning equation in these circumstances is invalid. Leopold, Wolman and Miller point out that surface roughness (n) is not independent of hydraulic radius (r). In the case of the Avana Valley the shallow flows postulated by Farrington and Bellwood would lead to great variations in roughness, especially if the canals were heavily vegetated, rendering inappropriate the use of either formula to calculate average velocity.

This aside for the moment, taking account of the probable vegetated nature of the shallow channels, a roughness coefficient of 0.035 to 0.1 can be assumed (Leopold, Wolman and Miller *ibid,* Henderson 1963:99). The value Farrington and Bellwood used was apparently 0.03, as for the Halawa Valley (*ibid*:123).

Farrington and Bellwood (*ibid*: 122) state that 'For an excavated channel, the area of the wetted cross-section (A), the wetted perimeter (WP), and the channel slope (s) *must be accurately measured* . . .' In the case of the Avana Valley surveys however (*ibid*:124), 'No channel cross-sections were drawn during the survey, but *photographs suggest* a trapezoidal cross-section with a base width of 35cm'. Given that the data came from a photograph it is not unreasonable to assume that the base width of the canals was not exactly 35cm, but lay perhaps between 30 and 40cm. In this case a range of possible values for discharge (Q) can be estimated based on Farrington and Bellwood's assumption that the depth of water in the channels was between 1 and 5cm. Table 1 lists the results obtained by calculating discharge for a range of likely roughness coefficients and depths.

Using the Manning equation presented above for depths of 1, 2, 3 and 5cm of water the range of discharges obtained using different roughness coefficients alters considerably the values for any given depth.

Depth (cm)	Discharge range m^3/sec
1	2×10^{-4}—8×10^{-7}
2	6×10^{-4}—2×10^{-6}
3	1×10^{-3}—4×10^{-6}
5	3×10^{-3}—1×10^{-5}

As suggested previously however, at such shallow depths the concept of average velocity as expressed by the Manning equation is virtually meaningless. At best, given the various assumptions made throughout the analysis it would appear to be spurious scientism to extend the values beyond one significant figure. Spitting into the canal in the Avana Valley at a flow of 0.00013 m^3/sec for instance could have altered the flow to 0.00015m^3/sec. No allowance has been made for either infiltration or evaporation losses from the canals yet at shallow depths on a relatively broad canal both would be high. For the Halawa Valley example Farrington and Bellwood allow 10% for such 'conveyance losses' (*ibid*:123), but none for the Avana Valley examples. If 10% were allowed for the Avana Valley as well, operating depths for the canals to match the irrigation requirement (IR) and HLR for the pondfield systems would not be of the order of 2cm or less (*ibid*:126) but, from Table 1, as much as 5cm, an underestimate by Farrington and Bellwood of more than 200%.

It also seems unlikely that the canals were in fact dug into volcanic tuff (*ibid*:124), a sedimentary rock having the general consistency of sandstone. To have dug a canal at least 50cm wide and deep to carry between 1 and 5cm (or even 10cm) of water through such a rock seems unreasonable, when an adequate dam and spillway system could have diverted floodwaters away from the system without nearly so much expenditure. It is probable that the canals were actually cut into much softer volcanic ash or surface soils or regolith, and that in fact infiltration losses during transmission were thus significant.

Despite these criticisms however, the concepts expressed in the paper are important. As Farrington and Bellwood conclude there is indeed a need for more study of the hydrology of contemporary systems, although it is not valid to contend that there is an absence of any research on this (*ibid*:126). The work of Watson (1970) and Earle (1978) which they quote, as well as Kirch (1975:286-7) are examples. It is true that archaeologists working in the Pacific have until now largely ignored the extra information which can be obtained using the principles of open channel hydraulics. While writers such as Riley (1975) and Kirch (1977) have used the HLR measure, none has previously attempted to assess channel flow from the archaeological data of channel cress-sections. Such principles, when *correctly* applied, will indeed give a much better understanding of the functioning of prehistoric taro irrigation systems in the Pacific, and allow comparisons between them.

Depth assumed (cm)	Est. mean width (cm)	Calculated discharge values (m^3/sec.) using roughness values of: 0.03 (unveg.)	0.035 (light veg.)	0.1 (heavy veg.)
1	30	2x10^{-4}	2x10^{-4}	4v10^{-7}
2		6x10^{-4}	5x10^{-4}	2x10^{-6}
3		1x10^{-3}	9x10^{-4}	3x10^{-6}
5		3x10^{-3}	2x10^{-3}	8x10^{-6}
1	35	2x10^{-4}	2x10^{-4}	8x10^{-7}
2		6x10^{-4}	6x10^{-4}	2x10^{-6}
3		1x10^{-3}	1x10^{-3}	4x10^{-6}
5		3x10^{-3}	3x10^{-3}	8x10^{-6}
1	40	2x10^{-4}	2x10^{-4}	8x10^{-7}
2		7x10^{-4}	6x10^{-4}	2x10^{-6}
3		1x10^{-3}	1x10^{-3}	4x10^{-6}
5		3x10^{-3}	3x10^{-3}	1x10^{-5}

Table 1. Range of Q values obtained using data published for Avana Valley, Rarotonga and calculated by Manning formula, using an averaged canal gradient of 3.8% (Farrington and Bellwood 1980:125). * Roughness values after Leopold, Wolman and Miller (1964), Henderson (1963).

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. . . . and by each cleft there was a stream of water[1]. Reply to Spriggs and Sullivan.

I. S. Farrington

Department of Prehistory & Anthropology
Australian National University, Canberra.

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Spriggs and Sullivan comment in their final sentence on our paper: 'such principles when *correctly* applied will indeed give a much better understanding of the functioning of prehistoric taro irrigation systems in the Pacific and allow comparisons between them'. I fully concur with this statement. Yet it implies that Spriggs and Sullivan understand and *correctly* apply the principles of open channel hydraulics and hydrology, but sadly this does not appear to be the case. I wish to clarify a few minor points and discuss the effect of vegetation on canal flow and its calculation.

Firstly, at no point was the approach adopted in our paper claimed to be 'novel'. In fact a list of references was published indicating where the principles of open channel hydraulics and/or hydrology have been utilized in the analysis of prehistoric canals elsewhere in the world. References on pondfield taro systems which describe water use and hydrology were also supplied. Since our paper was written, papers by Kirch (1977, published 1980) and Earle (1980) have appeared, further enhancing this descriptive literature.

To cite a Public Works Engineer's description of an irrigation sytem for 'island-bed' taro cultivation in Milne Bay Province, PNG, is a gross misunderstanding of the history of the use of open channel hydraulics, of the training such engineers and agricultural officers received, and the roles they played in recording indigenous agriculture in many parts of the world. I suspect that the literature is full of such reports describing active irrigation systems.

The use made of the Milne Bay description leads to a number of misunderstandings and misrepresentations of our paper. This particular system is not a pondfield one. Spriggs (1980) has distinguished four types of taro irrigation system on the basis of the method by which water was applied to the field. He records no pondfields on mainland PNG and notes that the Milne Bay coastal strip is characterized by island bed systems in which 'water is led round the perimeter of usually rectangular beds . . .' (p. 16). He goes on to say that 'a pondfield system here would perhaps not allow sustained production on these soils. In addition, the terrain on the plains may be unsuitable for pondfield agriculture. On near level ground, flow would be sluggish and water temperature would perhaps increase to levels where Pythium corm rot would not occur' (p. 8). Thus, hydrology of this system *cannot* be compared with pondfield systems, nor can the Hawaiian legal requirement, derived for pondfield taro systems, be used in its analysis. However, there is an urgent need for research on the hydrology of other types of irrigated taro systems.

Spriggs and Sullivan also use the Milne Bay description to raise the question of the effect of vegetation on canal velocity and discharge. They note that flow was reduced by 40% in a vegetated channel and that to use an unvegetated channel in the equation provides a serious 67% overestimate of discharge. They suggest that we 'do not take account of this critical factor when calculating co-efficients of surface roughness . . .' (p. 3). They are correct in assuming that an n value of 0.030 was selected for the

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[1] The title of this paper is taken from the account of Gomez Hernandes Catoira, who was chief purser and official chronicler of the fleet under the command of General Alvaro de Mendaña on a voyage of discovery in the South seas. It was written on 17 May 1568 and is one of the earliest European descriptions of irrigated taro terraces (Lord Amherst of Hackney and Thomson 1901:II, 306).

analysis. However, they are incorrect in stating that vegetation in the canal was not considered. Spriggs and Sullivan state that Leopold, Wolman and Miller (1964:157-158) suggest that a value of 0.035 and 0.040 would be more appropriate to account for vegetation growing in canal bed and banks. However, I can find no such reference in Leopold, Wolman and Miller to this detail either on the pages referred to or anywhere else in the book! But this is merely an incidental point. Tables of the roughness co-efficients ($\underline{n}$) are available (eg. Barnes 1967; Chow 1959:110-113, Israelson and Hansen 1962), and I have selected the most relevant to this study (Table 1).

Type of Channel	Min.	Normal	Max.
Excavated or dredged			
a. Earth, straight and uniform with short grass and few weeds	0.022	0.027	0.033
b. Earth, winding and sluggish			
grass with some weeds	0.025	0.030	0.033
dense weeds	0.030	0.035	0.040
earth bottom, rubble sides	0.028	0.030	0.035
d. Rock cuts			
smooth and uniform	0.025	0.035	0.040
e. Channels not maintained, weeds and brush uncut			
dense weeds, high as flow depth	0.050	0.080	0.120

Table 1. Values of the Roughness Co-efficient ($\underline{n}$) (after Chow 1959).

The Halawa Valley Complex 1 canals cannot be regarded as winding and sluggish and the excavated cross section has an earth bottom with rubble banks. Therefore an $\underline{n}$ value of 0.030 seems appropriate. Furthermore, frequent canal cleaning once, twice or more a year, will serve to keep the $\underline{n}$ value low. The Avana Valley canals have fairly steep gradients and relatively swift velocities and thus the effect of vegetation on flow would be limited. Contrary to Spriggs and Sullivan, these canals are indeed cut into rock (Bellwood 1978:84). Therefore if these bed and bank characteristics are considered, an $\underline{n}$ value of 0.030 again seems satisfactory. Chow (1959:179) has noted that in all small earth canals '. . . lining of grass is often found to be advantageous and desirable . . .' because it reduces erosion and silting. No maintenance system is going to fully eliminate grass or weeds from a canal and thus an $\underline{n}$ value of 0.030 can be considered to describe the canals analysed in our original paper. The realisation of this factor therefore renders Spriggs' measurement of velocity measured in the field comparable with those velocities derived for abandoned channels.

Let me now examine the effect of vegetation on canal flow and on the hydrology of pondfield taro systems. As stated previously, I consider an $\underline{n}$ value of 0.030 as an appropriate working value for both the Halawa and Avana Valley canals assuming that these were cleaned once or twice per annum. If the maintenance frequency were lessened and values of 0.035 and 0.040 became the appropate working values for the canals, the effect on canal discharge would result in reduction of only 15% and 25% respectively.

The effect of these on pondfield sytems is quite minimal. For an Avana Valley canal, 35cm wide and flowing at 2cm deep throughout, this represents a reduction of 0.49 and 0.85 litres per second. Neither of these reductions places the system in jeopardy. I have already stated that the ratio of irrigation requirements (RI) to input indicates for this valley, and elsewhere in Oceania, a surplus of 84-93% which serves as throughflow maintaining the pondfield environment for successful taro cultivation (Farrington and Bellwood 1980:125). The Avana Valley canal with an $\underline{n}$ of 0.040 would still have an 84% surplus and thus maintain cultivation.

It is only when a canal is very poorly maintained and choked with tall weeds, roots and shrubs ($\underline{n} = 0.05$) that a reduction in discharge of 40% is achieved. The Milne Bay canals were not maintained for cultural reasons and fed island-bed gardens which were abandoned after 5 years (Kahn 1979). This merely substantiates my earlier points on the incomparability of this system with pondfield ones. If $\underline{n}$ were 0.1, the reduction in flow would be 70%. The impact of this on the system would be to reduce its ability to withstand a period of drought and to reduce the amount of throughflow. The system would therefore be more susceptible to pest and disease infestation, but in the absence of prolonged drought, be quite capable of producing an economic crop.

The final point I wish to raise concerns the phrase 'correctly applied . . .' and the Manning Equation. I note that in the two left hand columns in Spriggs and Sullivan's Table 1 the figures differ by about one order of magnitude from the figures in Table 1B of the original paper (Farrington and Bellwood 1980:124) for reasons independent of a change in value of surface roughness. I also found it impossible at first to reconstruct their figures using either their revised Manning formula or the original. The reason for this discrepancy is quite simple and concerns the number of zeros after the decimal point, when centimetres are written as metres. A subsidiary, and bemusing fact, is that this error does not occur in the solution of both the Manning and the Discharge equations, but only in the former. In the Manning equation depth (d) appears to have been consistently written with an extra zero after the decimal point, e.g. 5cm = 0.005m. This figure was then taken to the two-thirds power and velocity calculated. This answer was then multiplied by width and the correct depth (0.05m) to obtain discharge. I do not wish to bore the reader with another table, simply request that the last line of the Spriggs and Sullivan Table (i.e., width 40cm; depth 5cm) be compared with my revised and *correct* calculations for each of the three values of $\underline{n}$. My results are 0.018, 0.015, and 0.013, respectively. These are of the same order of magnitude as those in our original table.

This is an elementary mistake but one which renders their comments even more ridiculous. Even those with a rudimentary knowledge of mathematics should realize that if canals are measured in centimetres, and if there are 1000 litres in a cubic metre, then discharge may be written in either litres per second (l.sec^{-1}) or cubic metres per second ($\text{m}^3\ \text{sec}^{-1}$), e.g., $4.5\ \text{l.}\ \text{sec}^{-1}$ is equal to $0.0045\text{m}^3\ \text{sec}^{-1}$.

The right hand column of the table differs from my calculations, using $\underline{n} = 0.1$ and the same data, by three orders of magnitude, e.g., at 30cm width and 5cm deep my revised calculation is 4×10^{-3} (cf. Spriggs and Sullivan Table 1). The reasons for this error are not apparent to me, but the error renders their figures totally meaningless.

The correct application and understanding of the methods of analysis as outlined in our original paper will broaden knowledge of prehistoric pondfield taro hydrology. Our methodology and results need to be rigorously tested and this could begin with analyses of the more recently published systems. Clearly comments, such as those of Spriggs and Sullivan, serve only to delay advance in our understanding by offering spurious arguments supported by mathematically incorrect sets of results. My rejecton of the Milne Bay data on the grounds that it does not refer to pondfield irrigation suggests that future research should concentrate on the hydrology of other types of taro irrigation systems.

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