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Improving Irrigation Policies: "Designer" Irrigation Consents and Soil Hydraulic Properties

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Abstract

The concept of "designer" irrigation consents is introduced. Such consents would be based on a "best match" between the intrinsic hydraulic properties of the land, the water requirements of the crop being grown, and optimal irrigation management.

This paper proposes a method for evaluating soil hydraulic properties from existing data. Soil hydraulic "Building Blocks" of data from reference sites are used to represent a soil profile, and to model water infiltration and movement.

Using this "Building Block" approach, two contrasting soils from the Heretaunga Plains, Hawkes Bay, (Twyford and Mangateretere) were evaluated. Measured data from representative locations were compared with assigned "Building Block" data for two simulation scenarios - a 365 day, day by day, water balance for the whole profile (to 1.2 m depth), and drainage from a saturated soil profile. Results showed that numerical simulations using the "Building Block" approach conformed satisfactorily with those using measured data, in three of the four cases. The approach may thus be useful in allocating water in a "designer" consent process, and a more detailed and critical evaluation of the approach is warranted.

Introduction

A sound scientific basis is needed for irrigation consents (water permits / water rights) under the Resource Management Act 1991, to avoid inefficient use of water and energy (for applying the water), and to decrease risk of groundwater contamination through the leaching of pesticides and fertilisers. A survey of existing New Zealand policies (Dravid et al., 1995) indicates, however, that often the only basis for existing water permits is a perceived water-need of a crop (some 3-5 mm/day), that land and soil factors are not considered, and that there is currently no incentive for growers to use less water than that allocated.

This paper introduces the concept of "designer" consents for water allocation, based on the ability of the land and soil to accept, store, and transmit water, the water need of the specific crop, and the water application and management system used. The focus of the paper is on soil hydraulic properties; crop needs and the management and application systems are not considered in detail.

Water Permits and Current Policy

In the past, water permits have recorded the users of water, and have generally set broad maximum limits on extraction. No attention has been given to the issues of aquifer protection and the allocation of a finite resource.

Current water allocation policy has been recently reviewed (Dravid, et al., 1995). Of the 14 Regional and Unitary authorities in New Zealand, eight were found to have no policy at all. For the six authorities that did have some form of policy in place, all related to an assumed 'need' or demand for water; three had different policies based on crop type, two had limits on the maximum quantity allocated, and one had a policy based on the nature of the source aquifer. A need thus exists for improving the consent procedure to promote aquifer protection as well as for allocating an increasingly scarce resource.

Irrigation Efficiency

All forms of irrigation are inefficient, and some wastage is inevitable; different kinds of inefficiency have been identified by Painter and Carran (1978). While all wastage is of concern, the "distribution pattern efficiency" (the ratio of the water applied to the water retained within the root zone) is particularly relevant to this paper. This "efficiency" (really an "inefficiency") is reflected in the mass balance of inputs or outputs to the root zone; the applied water, particularly that from high-intensity spray systems or flood systems, is rarely accounted for within the root zone. This "inefficiency" is even used as an indicator of a "thorough soak" when, for example, irrigation is continued until there is a good flow from the tile drains!

There are two broad mechanisms of water loss. "By-pass flow" (Bouma, 1984) through macropores occurs where ponding at the soil surface causes gravity movement down through biopores and cracks, through an otherwise unsaturated matrix. Macropore flow and preferred pathways of water movement have received significant attention in recent years (e.g. Scotter, 1978; Bouma, 1981; Beven and Germann, 1982). The reduction of "by-pass flow" is possible by reducing the *rate* of application so that no surface ponding occurs. Water application rates less than 10 mm/hr are often required. Across a paddock hydraulic conductivity varies very much less for "near-saturated" conditions than that at saturation (Watt and Crouchley, 1985). Where drainage is the result of non-uniform water application, growers may correct the problem through the routine checking and calibration of nozzles, and monitoring equipment performance. This in itself may be part of the "designer" consent approach.

Drainage from the base of a saturated soil profile (or from the "bottom" of the root zone) occurs in response to the total potential energy gradients that are set up in the profile by the percolating water. Whether or not it is helpful to think of this as "piston flow" depends on the complexity and hydraulic continuity of the system. This "drainage" is the output from a profile where the storage has reduced to zero. Drainage volumes can be reduced by controlling the *duration* and *total volume* of application.

No known studies have quantified the volumes passing to depth under active irrigation. Indeed, the contribution of natural rainfall to direct aquifer recharge also deserves attention. Up to 20% bypass flow in summer months is reported by Bouma and de Laat (1981), and responses in less than 2 days at 2.4 m depth are reported by Germann (1986). Gross drainage can be roughly assessed from differences between annual rainfall and annual evapotranspiraton. That "bypass flow" and "drainage" occur with natural rainfall is not a reason for dismissing the need for irrigation control. Nutrients and agrichemicals should be retained near the surface for degradation or uptake in the rhizosphere, rather than flushed out by irrigation.

New Zealand's escape from groundwater pollution, and over-exploitation of and structural damage to aquifers is perhaps more good luck than good resource management (Brown, 1991), but pesticide contamination of groundwater is now being reported (Close, 1993). Significant landscape "capacitance" may be buffering adverse impacts that will become apparent only in the future.

"Designer" Irrigation Consents

The concept of "designer" irrigation consents recognises the uniqueness of each irrigated area, and strives to provide a "best match" between the hydraulic properties of the land, the water requirements of the crop being grown, and optimal management and irrigation methods. Such a consent would be unique to a management block, be it a paddock of process tomatoes, a vineyard, a pip-fruit orchard or block within an orchard, or an irrigated grass paddock. A "designer" consent addresses not only the volume of water allocated for irrigation, but also the irrigation schedule, and the rate and duration of water application.

One option for implementing "designer" consents is through the use of land-owner Water Management Plans whereby applicants demonstrate awareness and knowledge of their land-crop-management system, and apply for only such water as can be optimally used. This would require knowledge of crop water requirements, the current performance of the irrigation system (including recent calibrations of sprinker nozzles), the relationship of the block to known aquifers and water ways, and the hydraulic nature of the soil. The rate and duration of irrigations would be specified, and the method of scheduling stated. The onus for the preparation of the Water Management Plan would be on the applicant, who may choose to be assisted by irrigation consultants. Guidelines would have to be prepared by the local council who would also have their own criteria for approving the plans. These guidelines may vary depending on the hydro-geology of the area, e.g. a high-risk unconfined aquifer recharge area would be likely to have more stringent criteria than some other areas. Once operational, the bureaucracy involved would not need to be more than that under the present system.

Conventional irrigation permits or resource consents typically addreses *who* has applied (name, location, postal address), *from where* the water is to be taken, the *rate* of extraction (eg litres per second), the *purpose* of the extraction (e.g. "to irrigate 8ha of crops and pasture"), and a *location of the irrigated area* by a map grid reference.

A "designer" consent, would authorise the taking of water in accord with the Water Management Plan tabled at the time of application. It addresses the *consequences* and *effects* of the irrigation and thus affirms the philosophy of the Resource Management Act. The "designer" consent would acknowledge the Water Management Plan as the guide document. A similar procedure is successfully operating in South Australia (M. Smith, pers comm).

Quantitative Land Evaluation

Field and laboratory measurements of soil properties can be very costly. A basic issue in the "designer" consent concept is thus how to make best use of *available* information. Following the concepts of Bouma (1989), this should be done in ways that not only make best use of the New Zealand Soil Classification (Hewitt, 1992), but which are also appropriate to the more quantitative demands of contemporary land use.

To use existing data it is necessary to determine what the individual parameters really mean, what kind of latitude is significant, and to correlate indicators and parameters in interpretations. The *pedofunctions* of Lamp and Kneib (1981), and the *transfer functions* of Bouma and van Lanen (1987) are procedures that have been suggested for making these translations. *Pedotransfer functions* (Bouma, 1989) relate different soil characteristics and properties with one another or to land qualities. Thus, soil characteristics such as horizon thickness, structure, etc. and land characteristics such as 'water table' can lead to the estimation of a land quality such as 'soil water deficit'. A number of functions might be used to derive a specific land quality. Pedotransfer functions may be 'continuous' (e.g. horizon thickness, % clay) or 'class' functions (e.g. horizon code; watertable). The functions themselves range from simple correlations to more complex models and algorithms.

The purpose of our study was to investigate the prediction of hydraulic properties of a soil from available information and data. From a minimal sampling by hand auger of a management unit (e.g. a paddock in commercial tomato production), could sufficient information be quickly gathered to identify the essential soil features of the paddock and to decide whether these matched known soil types, and could the principal hydraulic properties be quantitatively inferred from existing data on the soils?

For soil characteristics to be truly incorporated in a "designer" irrigation consent, the hydraulic character of the soil must be expressed in a quantitative manner. One method is by modelling, using vertically arranged soil hydraulic "Building Blocks", based on existing data for soil types, to predict water movement in soils for which no direct (*in situ*) hydraulic information is otherwise available. The "Building Block" approach is an approximation but it could be a great deal more economic than direct measurement, and more realistic than a purely qualitative approach.

Method

Two soils with different hydraulic properties were selected for study. In summary, we started with field areas of about 10 ha that had been previously mapped at a coarser scale, and validated the soil types by grid augering across the area. Representative soil profiles were identified from this augering (see later) and hydraulic properties were assigned to these profiles by a matching procedure with data from a soil physical database built up from earlier studies in the Hawkes Bay area. This procedure is subsequently referred to as the "Building Block" method. We then obtained additional *on-site* soil physical and hydraulic data by digging one pit (in each soil) and sampling as appropriate to 1.2 m depth. Two alternate sets of hydaulic data were thus obtained for each soil, an on-site measured set, and an inferred-by-matching "Building Block" set. These alternative sets were then compared by considering their respective response to numeric simulation through time of two different moisture scenarios.

This study is a preliminary assessment of whether more detailed studies on the "Building Block" approach are warranted. At no stage was drainage measured directly, and at no stage did we undertake direct correlation of soil physical properties. Any difference between the two profiles that was significant in field terms should be best reflected in the numeric simulations.

Representative Soil Profiles

Two management units were examined; one was part of an apple orchard, the other a tomato paddock. For at least four sites in each unit, soil observations were made by examining hand auger samples. The various layers, to depths of around 1.2 metres, were described according to texture, colour (with special attention to mottling and grey colouration caused by waterlogging), and permeability class (Table 1). The permeability class was assigned to each layer based on features such as consistence and porosity, using procedures modified from Griffiths (1991).

By reviewing the features and variability of the soil in each management unit, a single representative "profile form" was outlined. This field profile had three layers (topsoil, upper subsoil, and lower subsoil) for which texture determinations and permeability class estimates were made. In the final and critical step we verified the soil series.

The field profile was therefore an integrated but simplified expression (based on a number of augered observations) of a three-layered profile (topsoil, upper subsoil, lower subsoil) that contained information on the permeability class, texture, position in the profile, and soil series.

For areas with spatially complex soil patterns, or for larger management units (say twenty hectares or more), it may be necessary to divide the area into two or more representative units. Subdivision may already be recorded on soil maps where soil phases are recognised. However, during preliminary development of the procedure using 50 paddocks, subdivision was necessary in only a few cases.

The two field profiles in this study were on floodplains and were therefore Recent Soils. Their moisture release data can be satisfactorily predicted from their texture. For other soils, more would depend on specific horizon identification (eluvial, argillic, fragic, etc.), and pedality.

Soil Hydraulic "Building Blocks"

Soil hydraulic "Building Blocks" were assigned to each of the three layers (topsoil, upper subsoil, lower subsoil) of the field profile. These so called "Building Blocks" were simply a collection of hydraulic parameters taken (or derived) from an existing soil physics database. In this study a simple matching approach was used. Starting with the topsoil unit of the representative field profile, and knowing the Soil Series (e.g. Twyford), all "A horizon Twyfords" present in the database were inspected, and the "best match" was identified.

The information for a "Building Block" pertained to the moisture release curve (the relationship between matric potential and water content), and any recorded hydraulic conductivity data. The hydraulic parameters followed Campbell's (1985) functional description of the moisture release curve, and were:

TABLE 1— Relationship of the field estimate of permeability with permeability class and hydraulic conductivity

Field Estimate of Permeability ($mm\ hr^{-1}$)	**Permeability Class**	**Permeability Class Lower Boundaries (Hydraulic Conductivity)**		
		($m\ s^{-1}$)	**($mm\ hr^{-1}$)**	**($mm\ day^{-1}$)**
RAPID (**R**) [Upper limit: say 300+]	**Class 7:** VERY RAPID	8.3×10^{-5}	300	7200
[MOD. RAPID (**MR**) say 100]	**Class 6:** RAPID	3.9×10^{-5}	140	3400
	Class 5: MODERATELY RAPID	2.0×10^{-5}	70	1700
MODERATE (**M**) [Upper limit: say 70]	**Class 4:** MODERATE	5.6×10^{-6}	20	480
[MOD. SLOW (**MS**) say 10]	**Class 3:** MODERATELY SLOW	1.1×10^{-7}	4	100
SLOW (**S**) [Upper limit: say 1]	**Class 2:** SLOW	2.8×10^{-7}	1	24
	Class 1: VERY SLOW	[1.1×10^{-7} [1.1×10^{-8}	0.4 0.04	10]* 1]*
		Lower limit undefined		

Modified after Griffiths (1991).

* Included for convenience.

* **ThetaS:** (dimensionless, expressed as a fraction). The water content (cm^3/cm^3) at field saturation, where field saturation was approximated as (0.93 x total porosity).
* **b:** The slope of the straight line that approximates the moisture release relationship on a log-log plot.
* **Psi_e**: (cm). The matric potential at which the above line passes through the value ThetaS. Psi_e is the air entry water potential, i.e. the potential at which the largest water-filled pores just drain.

Measured Field Profiles

To obtain soil physics data from the management units, a pit was dug to 1.2 m and the soil was pedologically described. Procedures followed prescriptions by Milne et al. (1991) while horizon designations followed those of Clayden and Hewitt (1989).

At the same time as the soils were described, three key horizons in each pit were sampled. For determining the moisture release curve these horizons were sampled using a core sampler fitted with a drop hammer. Internal brass rings (diameter 50 mm, height 30 mm) facilitated the "undisturbed" sampling of duplicate cores. In the laboratory, techniques and procedures followed those outlined by Gradwell (1972). Water contents were determined at -1500, -100, -40, -20, -10, -5, and -2.5 kPa. Bulk density and particle density were also determined, and total pore space calculated.

Field sampling for hydraulic conductivity was also carried out. Stainless steel rings (diameter 98 mm, height 65 mm) were greased on their inner face. Using these rings hand carved cores were excavated vertically from a bench in each key horizon such that the core, when filled, was representative of the horizon. Four cores were taken from each horizon. Saturated and near-saturated hydraulic conductivities were determined using the method of Cook et al. (1993).

Numerical Simulations

Using CSIRO SWIM, a computer model for simulating soil water infiltration and movement through layered profiles (Ross, P. J. 1990a, 1990b), two soil water simulations were conducted using both "Building Block" model data and the measured and derived parameters from *in-situ* sampling. The performance of the integrated profile was considered more appropriate than statistical comparisons of the individual horizon parameters.

"Scenario 1" simulated a 365 day water balance commencing on 01 September with the soil at an initial -30 kPa tension throughout the profile. A time-series of daily rainfall for the period 1976/77 for Havelock North was used, this being a wetter than average year. "Scenario 2" simulated vertical drainage from the entire profile from an initial saturated state.

Results and Discussion

The soil profile from which the *in-situ* measurements were made is described in Figure 1, and the data from hand augering and the stack of soil hydraulic "Building Blocks" is shown in Figure 2.

For the Twyford site, a comparison of the "Building Block" model (Fig.2) and the measured profile (Fig.1) yields the following general observations:

a) The representation of the upper profile by two "Building Blocks" TB2 and TB3 to a depth of 45 cm is in broad agreement with the measured 0-36 cm. One "Building Block" would have sufficed. The field estimate of permeability (Table 1) of M (Moderate) was admitted with an assumed Ksat of 20 mm/hr on the basis of the database information. The measured Ksat (Fig.2) of 9 +/- 5.5 mm/hr was lower, but the two are arguably close given that hydraulic conductivity can range over at least three orders of magnitude.

b) The prediction of the lower profile by "Building Block" TB6 (45-120 cm) appears to be in general agreement with the measured 36-90 cm horizon, apart from the Psi_c parameter. The predicted permeability was correct. The 90-120 cm horizon was very similar to the horizon above and a single unit could have been taken to represent the full depth.

For the Mangateretere site:

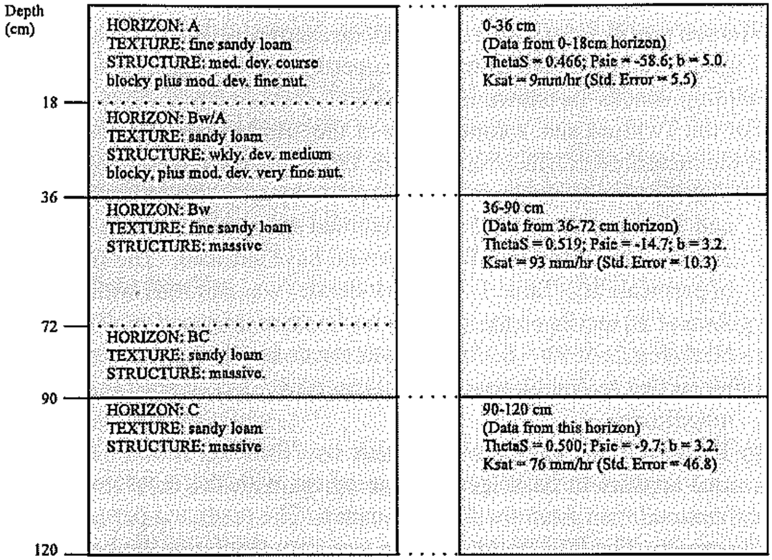
a) The prediction of the topsoil to 40 cm by "Building Block" MA2 appears reasonable, apart from the Psi_c parameter. The predicted permeability was low, though the variability of the measured values leaves some doubt as to their reliability.

b) The prediction of the upper subsoil to 90 cm by "Building Block" MA6 is accurate, except for the Psi_c parameter.

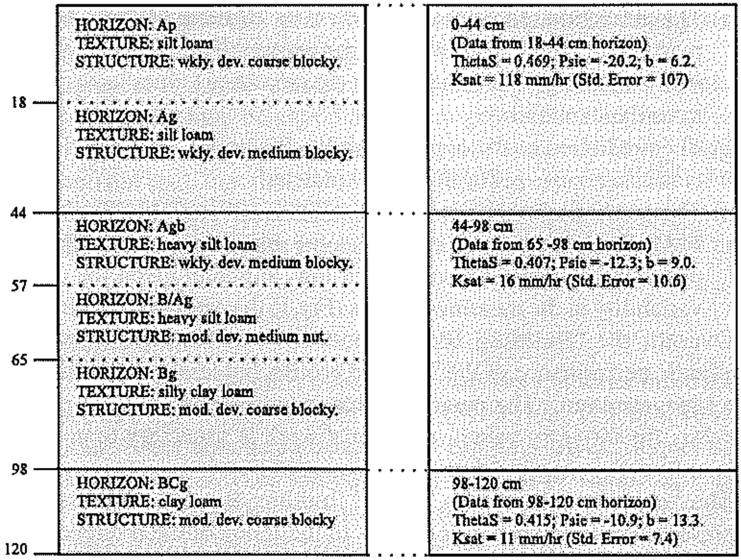
c) The prediction of the lower subsoil (90-120 cm) by "Building Block" MA8 is also out with regard to the Psi_c parameter. The predicted permeability could be considered low, although given the considerable variability in the measured values (Fig.1) the estimate is within the range.

Overall, the "Building Block" model is satisfactory in predicting the hydraulic performance of the Twyford profile, but less so in predicting that of the Mangateretere. The parameter that is most variable is not permeability, but Psi_c, the air-entry value. Additional work is necessary to understand the tolerance that is acceptable in this parameter.

The "best match" process, when "Building Blocks" are assigned to the representative field profile, is subject to the limits of the reference data base. On a confidence scale of 1-5 (1 = "not confident", 5 = "very confident") we would have ranked Twyford a "5", and Mangateretere a "3". The assessed field profile of the Mangateretere soil was considered less clayey and compact than the reference soil.



(a) TWYFORD
Left: Field Profile Description. Right: Meaured Values.



(b) MANGATERETERE
Left: Field Profile Description. Right: Meaured Values.

FIG. 1 — Field profile description and measured values: (a) Twyford, (b) Mangateretere.

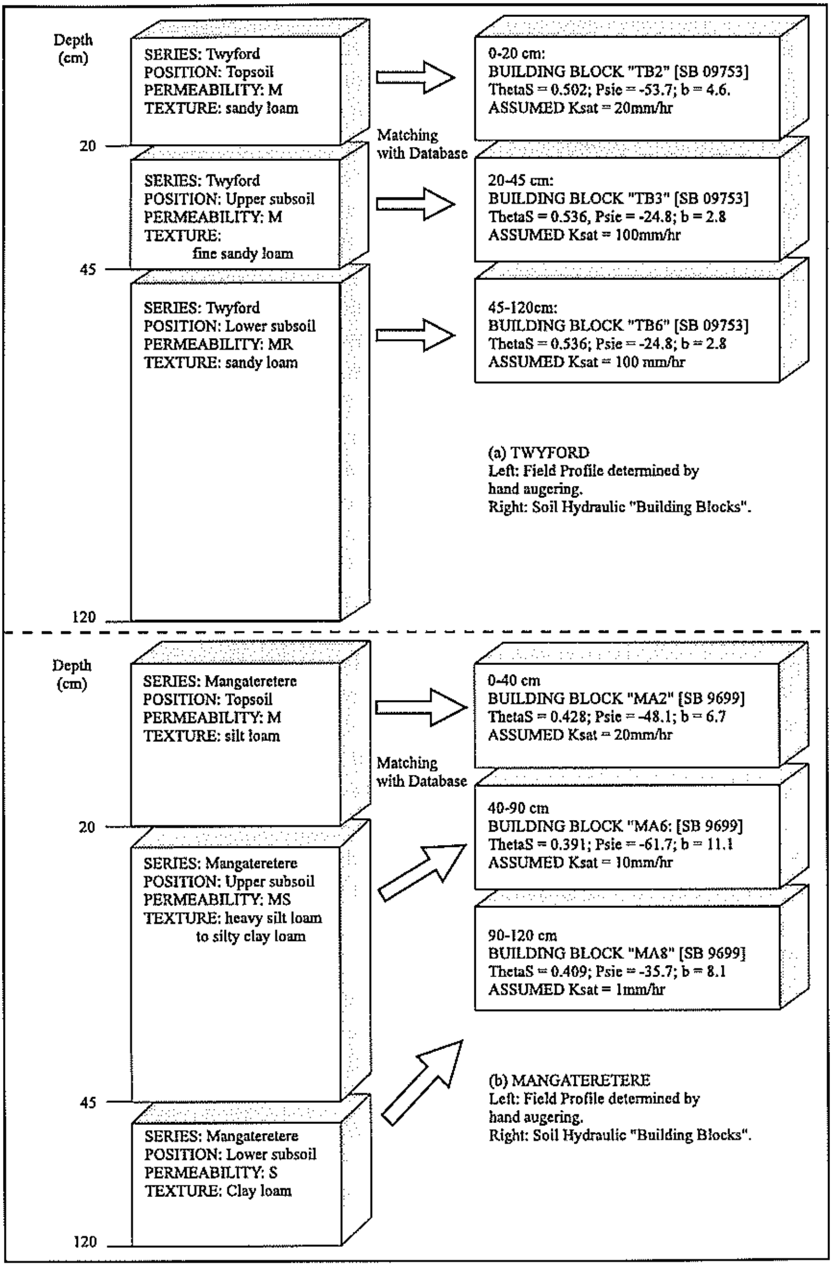


FIG. 2 — Field profile determined by hand augering and soil hydraulic "Building Blocks": (a) Twyford, (b) Mangateretere.

The 365 day water balance comparison (Table 2) shows that over the longer term, and through the variability of winter and summer, the broad regime of the water balance is similarly predicted by both sets of data. For both soils the *available water*, as accumulated through and referenced at the selected dates, is very similar. *Drainage* from the profiles is very similar for both sets of data for the Mangateretere soil. For the Twyford soil a difference carried through from the first three months relates mainly to the first 30 days when the profile was adjusting from the initial "start-up" matric potential of -30 kPa throughout.

In the second scenario drainage from saturated soil was calculated. Emphasis was therefore placed on the large pores with low tension. Here, greater difficulty in matching was expected because large changes in water content accompany small changes in tension. The results (Table 3) for both soils show a disparity between the "Building Block" and *in-situ* measured data sets. In the Twyford soil there is an immediate disparity in the total drainage after only 1 day. The 53 mm difference increases to only 75 mm after 365 days; after the first day the two drainages progress by similar increments which indicates a general similarity in hydraulic performance. The initial difference may reflect errors in defining field saturation (assumed at 0.93 of total pore space). The general agreement in drainage accrual *after* the first 1 day is important; it would be reasonable to ignore this period of adjustment in the energy gradients. For the Mangateretere soil the accrued drainages do not agree until after 100 days, i.e. 19(23) mm between day 100 and day 365. The "Building Block" and measured data sets show very different behaviours in the shorter time frame. Changing the saturated hydraulic conductivity rates in the "Building Block" set to those of the measured set helps but little (at 100 days the drainage was 46 mm compared to 21 mm, and 66 mm c.f. 40 mm at 365 days); the error may lie in the Psi_e discrepancies, and in the choice of "Building Block".

Conclusions

Carefully chosen soil physics data may emulate, through numerical simulation, the overall hydraulic performance of soils. The concept of soil hydraulic "Building Blocks" is useful, and their full evaluation for use with "designer" consents is warranted. In three of the four studies comparing the modelled outcome of scenarios, general agreement was demonstrated between soil physical data measured *in-situ* and soil physical data that was modelled. Where they did not agree there were some misgivings about the specific "Building Blocks" used.

Careful protocols must be established at the matching stage, i.e. when the "Building Blocks" are chosen from the data base. The 'best available' information will vary as to its appropriateness, and some measure of confidence should accompany the selection. A 1-5 subjective index is suggested.

TABLE 2 — Simulation of 365 day water balance from parameters determined using the "Building Block" model and the measured data (in parentheses): (a) Twyford, (b) Mangateretere

(a) Twyford

Parameter (mm)	**01-September to 30-November**	**01-September to 28-February**	**01-September to 31-May**	**01-September to 31-August**
Precipitation	250 (250)	422 (422)	678 (678)	1043 (1043)
Evapotranspiration	263 (263)	537 (562)	669 (695)	751 (777)
Available water	102 (129)	0 (2)	124 (125)	262 (285)
Unavailable water	92 (103)			
Drainage	95 (37)	95 (37)	95 (37)	240 (160)

(b) Mangateretere

Parameter (mm)	**01-September to 30-November**	**01-September to 28-February**	**01-September to 31-May**	**01-September to 31-August**
Precipitation	250 (250)	422 (422)	678 (678)	1043 (1043)
Evapotranspiration	263 (263)	507 (501)	639 (633)	721 (715)
Available water	72 (66)	0 (0)	123 (123)	198 (197)
Unavailable water	249 (223)			
Drainage	60 (56)	60 (56)	61 (57)	269 (266)

Sensitivity analyses are needed to determine the variability that is tolerable in the different physical parameters.

TABLE 3 — Simulation of drainage from saturation using the "Building Block" model and measured data (in parentheses):
(a) Twyford, (b) Mangateretere

(a) Twyford

Day	Drainage (mm)
1	209 (156)
10	296 (232)
100	369 (295)
365	402 (327)

(b) Mangateretere

Day	Drainage (mm)
1	0 (70)
10	4 (117)
100	21 (161)
365	40 (184)

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