Water and Solutes in Soil: Hydraulic Characterisation, Sustainable Production, and Environmental Protection

by

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DOCTOR OF SCIENCE

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STATUTORY DECLARATION

Environmental research, because of its complexity and multidisciplinary imperative, is best conducted by teams. Furthermore, the research environment in DSIR and subsequently in the CRIs has, over the last twenty years, been structured so as to ensure delivery of research results by teams. The work presented in this thesis has been carried out by teams of varying sizes, which has always involved me, and my colleagues.

However, throughout, for the work I have presented here for examination, I have played a leading role in the planning and the initiation of the research, the conduct of the experiments, the analysis of the results, the theory development, and the writing of the papers. I have been either the principal investigator, or at least an equal collaborator in all the projects that have been cited in Chapters 2-6, as well as in the majority of the papers in my appended *curriculum vitae*.

I declare that I have carried out, directed, or significantly assisted in all the work submitted here for consideration for the Degree of Doctor of Science. The assistance that I have received is clearly indicated by the joint authorship of the papers, and via the acknowledgements in those papers.

The following scientists have been part of the teams involved in the work presented in the body of this thesis.

Dr D.R. Scotter, Massey University
Dr J.P. Kerr, formerly of DSIR, Palmerston North
Dr I. White, Australian National University, Canberra
Dr J.H. Knight, formerly of CSIRO, Australia
Dr T.J. Sauer, USDA, Iowa
Dr S.R. Green, HortResearch, Palmerston North
Dr M.B. Kirkham, Kansas State University, Kansas
Ms J.E. McLean, Utah State University, Logan, Utah
Dr G.N. Magesan, Forest Research, Rotorua
Dr L.K. Heng, International Atomic Energy Agency, Vienna
Dr I. Vogeler, HortResearch, Palmerston North
Dr T.D. Heiler, formerly of NZ Agricultural Engineering Institute, Lincoln
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Dr B.H. Robinson, HortResearch, Palmerston North
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Mr M. van der Velde, University of Amsterdan, The Netherlands
Mr Th. Granel, formerly of ENITA de Clermont Ferrand, France

Dr C. Duwig, LTHE, Grenoble, France
Dr J.F. Roygard, Virginia Polytech, Blacksburg, Virginia
Mr C. van den Dijssel, HortResearch, Palmerston North.

Especial mention needs to be made of the extensive collaborative work with Dr Dave Scotter and Dr Steve Green, my colleagues and friends of long standing. All the papers I have presented in Chapters 2-6, are those in which I took a lead role. There are some other papers listed in my *curriculum vitae* in which either Dr Scotter or Dr Green was the significant researcher.

Signed ____________________
(Brent Euan Clothier, The Candidate)

Signed ____________________

JUSTICE OF THE PEACE FOR NEW ZEALAND J.P.

TABLE OF CONTENTS

ABSTRACT

The soil of the rootzone, the fragile and fertile interface between the atmosphere and the subterranean realm, is characterised by massive transfers of water and solutes. Our understanding of the biophysical transport processes into, and through, soil has been enhanced by the research endeavours of the applicant, Brent Euan Clothier.

Dr Clothier, a 1977 Ph.D. graduate of Massey University, has developed tools and techniques that increased the acuity of our vision of transport processes of water and solutes in soil, as well it has sharpened our ability to hydraulically characterise those mechanisms for the purpose of modelling and risk assessment. His research has also enhanced our understanding of how these biophysical processes affect sustainable agriculture, environmental protection, and the bioremediation of contamination. These endeavours are grouped, in this thesis, into four overlapping areas of research:

- Processes and properties of water movement into and through soil
- Processes and properties of solute movement through soil
- Root uptake processes and sustainable irrigation
- Plants, groundwater protection and bioremediation of contaminated soil.

The key elements of these four themes, and their contribution to knowledge, form Chapters 2-5 of this thesis. Dr Clothier's awards, honours, and impact are discussed in Chapter 6.

Chapter 1

INTRODUCTION

Soil, the fragile and fertile interface between the atmosphere and the subterranean realm, is characterised by massive transfers of water and solutes. Water and chemical fluxes through this porous medium of the soil, in the active presence of plants, are not only significant for the healthy functioning of soil as the clean and productive base for sustainable agriculture, but also they are critical for the role that the soil plays in protecting the environment of both our underground and surface reserves of water. Increasingly, fundamental knowledge of the biophysical functioning of rootzone soil is now being used to develop bioremediation techniques for either breaking down, or extracting contaminants from soil.

Our understanding of transport processes in soil has recently been enhanced thanks to two developments. New devices and techniques are providing better observations, at the local scale, of the state and fluxes of water and solute into, and through soil. Better theoretical understanding and new modelling techniques are being developed to extend and extrapolate these observations to realise improved understanding at larger spatial and temporal scales.

The research endeavours of the applicant, Brent Euan Clothier, have increased the acuity of our vision of transport processes of water and solutes in soil, as well heightening our ability to hydraulically characterise those mechanisms. These observations have permitted apposite parameterisation of the key transport processes, so as to allow mechanistic modelling of the nature and consequences of water and solute movement through soil. His research has also enhanced our understanding of how these biophysical processes affect sustainable agriculture, environmental protection, and the bioremediation of contamination. These endeavours are grouped, in this thesis, into four overlapping areas of research:

- Processes and properties of water movement into and through soil
- Processes and properties of solute movement through soil
- Root uptake processes and sustainable irrigation
- Plants, groundwater protection and bioremediation of contaminated soil.

These four themes respectively form Chapters 2-5 of this thesis. In each of these chapters, keynote papers published by Clothier and his colleagues, are discussed in relation to the critical elements of the works, and their contribution to knowledge. Copies of the full text of the papers cited are presented in logical order in Appendices A-D

Since his graduation from Massey University in 1977 with a PhD, Clothier's research has earned him many prestigious awards and significant honours, plus a host of editorial and academic positions of responsibility. These are discussed in

Chapter 6 of this thesis, along with a quantitative assessment of Clothier's scientific impact. A full *curriculum vitae* and complete list of Clothier's publications is listed in Appendix E.

Chapter 2

PROCESSES AND PROPERTIES OF WATER MOVEMENT INTO AND THROUGH SOIL

Papers cited in this chapter (See Appendix A for reprints)

A1 Clothier, B.E., D.R. Scotter and J.P. Kerr, 1977. Water retention in soil underlain by a coarse-textured layer: Theory and a field application. *Soil Science* 123: 392-399.

A2 Clothier, B.E. and I. White, 1981. Measurement of sorptivity and soil water diffusivity in the field. *Soil Science Society of America Journal* 45: 245-249.

A3 Clothier, B.E., J.H. Knight and I. White, 1981. Burgers' equation: application to field constant-flux infiltration. *Soil Science* 132: 255-261.

A4 Clothier, B.E. 1988. Measurement of soil physical properties in the field: A commentary. In "*Flow and Transport in the Natural Environment: Advances and Applications*". {Eds W.L. Steffen and O.T. Denmead.} Springer-Verlag, Heidelberg, pp. 86-94.

Soil is a layered medium, full of cracks.

Despite these annoying features, physicists first developed theory to describe water movement through soil by considering the medium itself to be uniform and isotropic. These theoretical schemes advanced our understanding of flow processes, but the imperative was then to incorporate the soil's characteristics of layering and macroporosity into models of water flow and storage, and to develop measurement devices to parameterise these rational schemes. Water in soil is, in a thermodynamic sense, either at negative potentials (unsaturated), zero potential (free water), or positive potentials (under a hydraulic head). For discontinuities in soil, such as vented macropores at the surface, or layering at depth, the state of soil's water is critical for deciding infiltration entry, and profile drainage.

Through the four papers cited in this chapter, Clothier advanced our theoretical understanding of the impact of layering and macropores on the entry and storage of water in field soils, and he developed tools to permit parameterisation of the controlling hydraulic properties.

Paper [A1]

When a coarse material underlies a finer-textured medium, the shape of the hydraulic conductivity function of the underlay, $K(\psi)$, controls the drainage of the overlying soil. Drainage across the interface ceases when the conductivity of the underlay becomes negligible, at say potential head ψ_i, when K there is small. Because profile drainage is then zero, the hydraulic head gradient in the soil above must become $\partial\psi/\partial z = 1$, where z is depth. In paper [**A1**], Clothier and colleagues, put all this information together, to arrive for the first time, at the general, explicit expression for the increase in stored water in the overlay, ΔW, above the depth to the layer, z^*, relative to what would be stored in a uniform soil of depth z^*. This they found to be

$$\Delta W = \begin{cases} \theta_s\left(-\psi_e\right)^{\lambda}\left[\dfrac{-\psi_i^{\,1-\lambda} - \left(z_i - \psi_i - z^*\right)^{1-\lambda}}{\lambda - 1 + \dfrac{z^* - z_i}{-\psi_c^{\,\lambda}}}\right] & \lambda \neq 1 \\[2ex] \theta_s\,\psi_e\left[\ln\left(\dfrac{\psi_i}{\left(\psi_i - z_i + z^*\right)}\right) + \dfrac{z^* - z_i}{\psi_c}\right] & \lambda = 1 \end{cases} \qquad [2.1]$$

where θ_s, ψ_e, and λ are the Brook & Corey parameters for the water-release curve of the overlay, and ψ_c is the potential at which drainage in the overlay soil would have otherwise materially ceased. This expression is plotted in Fig 2.1 which shows how the texture of the overlay (λ), and the cut-off potenial in the coarse underlay (ψ_i) can substantially increase the storage of water in a layered soil.

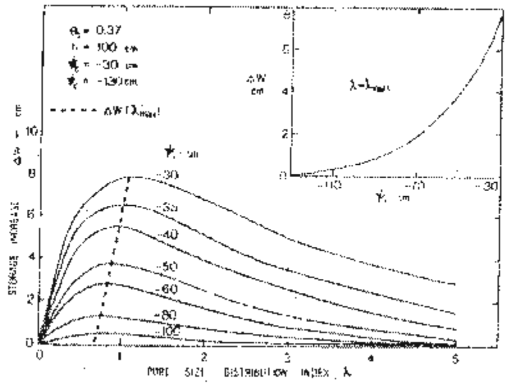

Fig 2.1 The increased storage of water in a layered soil in relation to the texture of the overlay, as represented by its pore size distribution index λ, according to its dependence ou the cut-off potential in the coarse underlay ψ_i (from A1 – Clotbier *et al.*, 1977)

This publication has been oft-cited. The Institute for Scientific Information (ISI) records that this publication has been cited over 27 times, which places it in the top 3% of cited papers (Garfield, E., 1985 *Current Contents* 43:3-8). Next, Clothier and his colleagues then developed a functional model for drainage through a layered soil, and they used the form of Eq [2.1] to explain the mottling that characteristically occurs just above coarse layer interfaces. The mottling is due to the higher-than-expected water contents above the interface because of the unsaturated cut-off in drainage as a result of the loss of conductivity in the underlay.

Paper [A2]

In 1979 and 1980, Clothier worked as a post-doctoral fellow at CSIRO's Pye Laboratory, studying unsaturated, flux-controlled infiltration into soil. Clothier and his colleagues, were, at first, unsuccessful in their field application of Philip & Knight's flux-concentration theory for constant flux rainfall. The field parameters they were measuring, gave predictions, in terms of the time-to-incipient-ponding, t_p, that were an order of magnitude in error. Clothier then realised that it was only the soil's matrix hydraulic properties that mattered prior to ponding, $t<t_p$.

The challenge then was to measure the soil's unsaturated properties in the range just below saturation. With his colleagues, a new device was developed whereby the pressure head of the infiltrating water could be controlled, so that apposite values of the soil's sorptivity and conductivity could be obtained. This, the first published such device, they called the sorptivity tube (Fig 2.2).

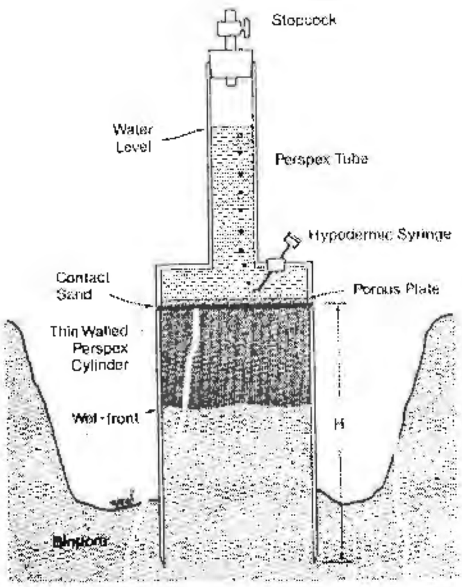

Fig 2.2 The sorptivity tube apparatus developed by Clothier and White (1981) [A2], to measure the hydraulic properties of the soil's matrix under unsaturated conditions.

This high-impact paper has been cited over 142 times, thus placing it in the top 0.33% of cited papers that have been referenced by peers in their publications (Garfield, 1985 *loc. cit.*). The sorptivity tube was the forerunner of the now-popular disc permeameters that are routinely used to measure the near-saturated hydraulic properties of soil. With these devices it is now possible to discriminate the macropore contribution to the soil's hydraulic character from that of the matrix.

Paper **[A3]**

In the 1930's Richards found the diffusive and convective flow of water through soil to be described by

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left(D(\theta)\frac{\partial\theta}{\partial z}\right)-\frac{\mathrm{d}K}{\mathrm{d}\theta}\cdot\frac{\partial\theta}{\partial z} \qquad [2.2]$$

This showed soil-water flow to be dependent on both the soil-water diffusivity function $D(\theta)$, and the hydraulic conductivity function $K(\theta)$, where θ is the soil water content. By using the sorptivity tube of paper **[A2]**, Clothier and his CSIRO colleagues found that the soil's matrix actually possessed a reasonably weak dependence on water content. This field information meant that the non-linear nature of the partial differential equation [2.2] might not be as strong as suggested by laboratory determinations on repacked soil. At the same time, John Knight had shown that if Eq [2.2] could be written as Burgers' equation, namely

$$\frac{\partial\theta}{\partial t}=D\frac{\partial^2\theta}{\partial z^2} - (A\theta+B)\cdot\frac{\partial\theta}{\partial z}, \qquad [2.3]$$

then a closed-form analytical solution could be found. Clothier, Knight and Ian White, in paper [A3], then used the sorptivity tube to find appropriate values of D, A, and B so that they could predict the evolution of water profiles under the constant-flux rainfall experiments that they had been carrying out in the field with a rainfall simulator. The success of these predictions is shown in Fig 2.3, where the measured penetration of the wet-front, appropriately scaled, was found to be in good agreement with that predicted by Burgers' analytical solution.

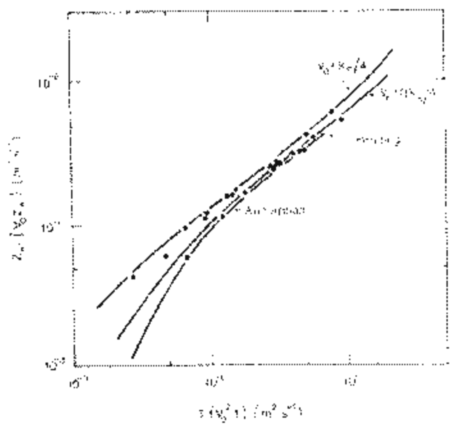

Fig 2.3 Prediction of the (normalized) penetration of the wet-front into soil using Burgers' equation (A3 – Clothier *et al.* 1981), in relation to observations made in the field during constant-flux rainfall

The advent of powerful computers has rendered obsolete the need for analytical solutions such as that of Burgers, but paper [A3] is oft-cited as it highlights the need for apt parameterisation of the soil's hydraulic character – irrespective of the means of prediction. Having been cited over 35 times in scientific publications (ISI), places this paper in the top 2.5% of cited papers (Garfield, 1985 *loc. cit.*).

Paper [A4]

At the Symposium held to celebrate 21 years of CSIRO's Pye Lab in Canberra, Clothier was invited to present an address on the measurement of soil physical properties in the field. This commentary was published in the Symposium book (paper **A4**). There Clothier discussed the belated recognition of the prime role played by surface-vented preferential flow pathways (Fig 2.2) which lead to rapid and far-reaching transport of water into and through soil. He concluded that new theoretical descriptions (paper **A3**), and appropriate measurements (paper **A2**) have given a more realistic appreciation of saturated/unsaturated water flow in field soil. In this commentary, Clothier lamented the then inability to incorporate, in a rational way, biological or biochemical processes in our descriptions or measurements of flow and transport in soil.

After this 1987 meeting, Clothier then attempted to address these concerns during his research projects over the next 15 years. These endeavours form Chapters 3-5 of this thesis.

Chapter 3

PROCESSES AND PROPERTIES OF SOLUTE MOVEMENT THROUGH SOIL

Papers cited in this chapter (See Appendix B for reprints)

B1 Clothier, B.E., T.J. Sauer and S.R. Green, 1988. The movement of ammonium nitrate into unsaturated soil during unsteady absorption. *Soil Science Society of America Journal* 52: 340-345.

B2 Clothier, B.E., M.B. Kirkham and J.E. McLean. 1992 *In situ* measurement of the effective transport volume for solute moving through soil. *Soil Science Society of America Journal* 56: 733-736.

B3 Clothier, B.E., L. Heng, G.N. Magesan, and I. Vogeler. 1994 The measured mobile-water content of an unsaturated soil as a function of hydraulic regime. *Australian Journal of Soil Research* 33:397-414

B4 Clothier, B.E., G.N. Magesan, L.K. Heng and I. Vogeler. 1995 In situ measurement of the solute adsorption isotherm of soil using a disc permeameter. *Water Resources Research* 32:771-778.

Soil lies astride the main thoroughfare along which rainwater enters our subterranean and surface water reserves. The water quality of these receiving bodies is thus strongly influenced by the solute transport processes and mechanisms of chemical exchange that prevail during the rainwater's passage through the biologically-active surficial layer of the globe - the medium we call soil. Development of sustainable systems of primary production and land protection also demands a proper understanding of solute transport processes in soil.

During the late 80's and early 90's, Clothier's research aimed to achieve a better analytical description of solute movement through soil, and sought to develop techniques so that theories of chemical transport could be parameterised.

Paper [**B1**]
Nitrogen movement through soil is an issue for effective use of fertilisers, as well as for environmental protection. Nitrogen is mainly transported through the rootzone either as the anion nitrate, or the cation ammonium.

In paper **B1**, Clothier and his colleagues developed an approximate theory, based on the method-of-characteristics, to describe the multidimensional flow of inert and reactive solute through soil. Separate miscible displacement experiments were used to parameterise the chemical exchange isotherms for nitrate and ammonium in two soils of differing cation exchange capacities. Independent one-dimensional experiments with the infiltration of ammonium nitrate were used to test the theory that had been developed.

Successful prediction was achieved of both the location, and dispersion, of the inert nitrate front, plus the invasion of the reactive ammonium. Using this theory, Clothier and Sauer then described the movement of urea away from drip emitters. In an invited address to the XIII International Soil Science Congress in Hamburg, Clothier cautioned about the use of urea fertigation in certain circumstances for he predicted, on the basis of his theory, that there can be a significant drop in pH right close to the emitter. This he corroborated with a series of experiments in the laboratory.

Paper [**B2**]

As noted in paper [A4], flow and transport processes in the field are quite different from those observed under uniform conditions in the laboratory. The deeper than expected penetration of chemical in the field led van Genuchten and Wierenga to propose, in 1976, a mobile-immobile model that could describe the fast and slow pathways for solute transport through soil.

This two-domain formulation for solute transport can be written as

$$\theta_m \frac{\partial C_m}{\partial t} + \theta_{im} \frac{\partial C_{im}}{\partial t} = \theta_m D_s \frac{\partial^2 C_m}{\partial z^2} - v_m \theta_m \frac{\partial C_m}{\partial z}, \qquad [3.1]$$

where C_m and C_{im} are the concentrations of inert chemical in the mobile and immobile domains and D_s is the solute dispersion coefficient ($m^2\ s^{-1}$). The only mechanism to transfer solute between domains is, for analytical convenience, limited to a diffusion-like process that can be described by

$$\theta_{im} \frac{\partial C_{im}}{\partial t} = \alpha \left(C_m - C_{im} \right) \quad , \qquad [3.2]$$

where α (s^{-1}) is the first-order mass transfer coefficient.

However, there was no direct way of observing either the partitioning into the mobile water fraction, θ_m, or its immobile complement, θ_{im}.

A direct means was first proposed by Clothier, Kirkham and McLean in this high impact paper [**B2**]

This technique used a tracer-charged permeameters to infiltrate chemical into field soil (Fig 3.1). Then by sampling the soil underneath, the resident concentration would reveal, if α were small, the mobile-immobile partitioning.

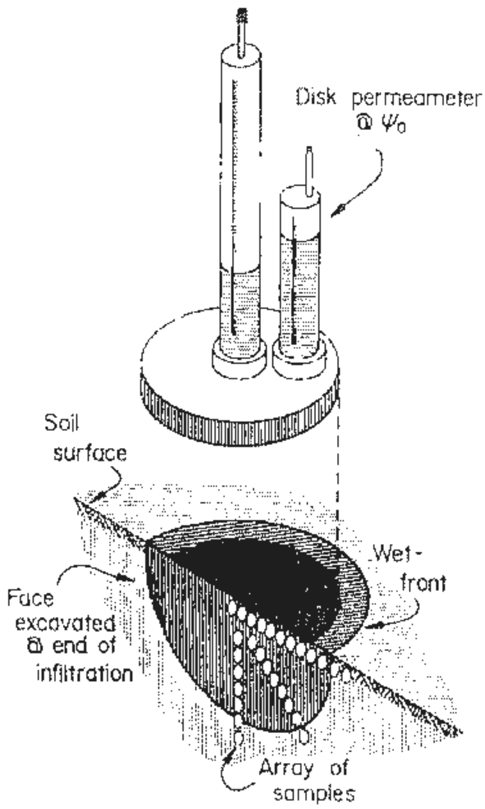

Fig 3.1 The set-up devised by Clothier *et al.* (1992) [B2] to employ a disc permeameters, and subsequent sampling underneath, to infer the soil's mobile water fraction, θ_m.

Samples taken from underneath the permeameters allowed the water content θ_o and tracer concentration c^* to be determined. The tracer solute in any sample would be partitioned between the two domains,

$$\theta_o c^* = \theta_m c_m + \theta_{im} c_{im} \qquad [3.3]$$

such that if interdomain exchange could be ignored during the period of infiltration, and if there were no tracer initially present in the soil (c_{im}=0), the soil's mobile water content can be found using the observations of

$$\theta_m = \theta_o \frac{c^*}{c_m} \quad . \qquad [3.4]$$

With this technique, Clothier and colleagues showed that, for Manawatu fine sand, the mobile fraction is only about half the soil's wetted porosity. Thus inert chemicals can be expected to travel twice as fast as would be expected from uniform theory.

This new technique has led to subsequent studies, by many others as well, that have sought to extend the utility of using permeameters to characterise solute flow through soil. In just a decade, this paper has been cited over 50 times (ISI), which places it in the top 1.2% of cited papers by colleagues (Garfield, 1985 *loc. cit.*).

Paper [**B3**]

Clothier and his colleagues, in paper [**B3**], then developed a variation of the measurement technique described in paper [**B2**], whereby they could measure the magnitude of the inter-domain exchange process, which is parameterised by α (Eq 3.2).

In this paper [**B3**], it was found that the diffusive inter-domain process for inert solute is likely to be rather weak. This was considered to be a result of the significant spatial distances that intensive sampling revealed between the mobile-flow pathways. It was concluded that convective interdomain exchange might be more important as a transfer mechanism for inert solutes between the mobile and immobile domains. Because of its rigorous assessment of the contrasting roles played by the two exchange mechanisms, this paper has already been cited over 22 times by other scientists, placing it in the top 3.5% of cited papers (Garfield, 1985 *loc. cit.*).

Paper [**B4**]

Next, Clothier sought to extend this technique so that permeameters could be used to measure, directly in field soil having a mobile-immobile porosity, the chemical exchange isotherm for reactive chemical. In paper [**B4**], Clothier and colleagues developed theory that could resolve, by assessing the relative penetration of fronts of inert and reactive chemical, and the differing resident concentrations, both the mobile-immobile partitioning, and the reactive adsorption isotherm. This theory could even handle non-linear reactive isotherms, such as the Freundlich form of,

$$S = m c^{n} \qquad [3.5]$$

where S is the adsorbed chemical concentration, and c is the solution phase concentration.

By linearising the isotherm at the influent concentration, and observing the position of the inert solute front, x_i, and the reactive solute front, x_r, the linear isotherm's distribution coefficient, K_D, can be determined from

$$R = 1 + \frac{\rho K_D}{\theta} = \frac{x_i}{x_f} \quad . \qquad [3.6]$$

In paper [**B4**], Clothier showed that by repeating experiments at two different concentrations c_1 and c_2, and observing the respective retardations R_1 and R_2, the non-linear isotherm (Eq 3.5) could be resolved, since

$$n = 1 + \frac{\ln\left(\frac{R_1 - 1}{R_2 - 1}\right)}{\ln\left(\frac{c_1}{c_2}\right)} \quad . \qquad [3.7]$$

Using experiments with bromide and sulphur-35 in a variably charged Ramiha silt loam, Clothier and his colleagues were able to determine the both the mobile water fraction, θ_m, and that they found that the exchange isotherm for ^{35}S to be S=2.3$c^{0.7}$.

In Chapters 2 and 3, the water flow and solute transport work of Clothier has been presented. These reveal that his endeavours have led to an enhanced understanding of rootzone transport mechanisms, as well as a better ability to parameterise them so that appropriate modelling can be carried out. Meanwhile, Clothier had also been concerned with the role of these process on sustainable irrigation practices (Chapter 4), and as well, he had been developing means to understand better the role of active root uptake of water and chemicals by plants (Chapter 4).

Chapter 4

ROOT UPTAKE PROCESSES AND SUSTAINABLE IRRIGATION

Papers cited in this chapter (See Appendix C for reprints)

C1 Clothier, B.E. and T.D. Heiler, 1983. Infiltration during sprinkler irrigation: Theory and field results. In "*Advances in Infiltration*" published by the American Society of Agricultural Engineers, Chicago, pp. 275-284.

C2 Clothier, B.E., K.R.J. Smettem and Pudjo Rahardjo. 1990. Sprinkler irrigation, roots and the uptake of water. In "*Field-Scale Water and Solute Flux in Soils*"[eds K. Roth, H. Flühler, W.A. Jury & J.C. Parker], Birkhäuser Verlag, Basel, Switzerland, pp 101-108.

C3 Clothier, B.E. and D.R. Scotter, 1982. Constant-flux infiltration from a hemispherical cavity. *Soil Science Society of America* 46: 696-700.

C4 Clothier, B.E., 1984. Solute travel times during trickle irrigation. *Water Resources Research* 20: 1848-1852.

The need for more-efficient agricultural use of irrigation water arises out of increased competition for water resources, and greater pressure for irrigation practices to be environmentally friendly. Within the rootzone, various physical, chemical, and biological processes interact to establish what fraction of the applied irrigation water is taken up by the crop, and they also determine the amount of chemical that the complementary fraction of water takes with it as leachates beyond the grasp of roots. Clothier was keen to see his theoretical and laboratory soil physics studies he was carrying out (Chapters 2 and 3), also having an impact on irrigation through the identification of sustainable practices.

Paper [C1]
In 1983, the American Society of Agricultural Engineers called a conference in Chicago on "Advances in Infiltration". Clothier and his engineering colleague Terry Heiler had their paper on infiltration during sprinkler irrigation accepted for presentation at this meeting. This work focussed on determination of the impact of the rate at which water was applied by sprinkling, V_o, relative to the soil's hydraulic conductivity, K_s.

Using theory developed in paper [**A2**], Clothier determined that for a rotating, or travelling sprinkler device with return period, t^*, that if $V_o/K_s>1$ then there would be

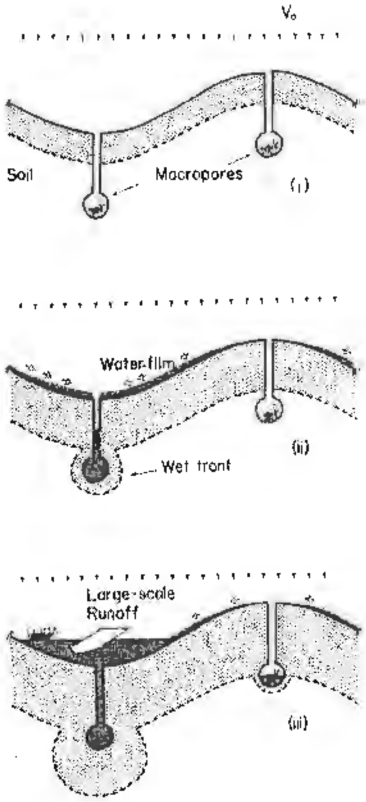

Fig 4.1 The sequence of hydraulic events leading to incipient surface ponding, and the generation of large-scale runoff under sprinkler irrigation, as proposed by Clothier & Heiler (1983) [C1]

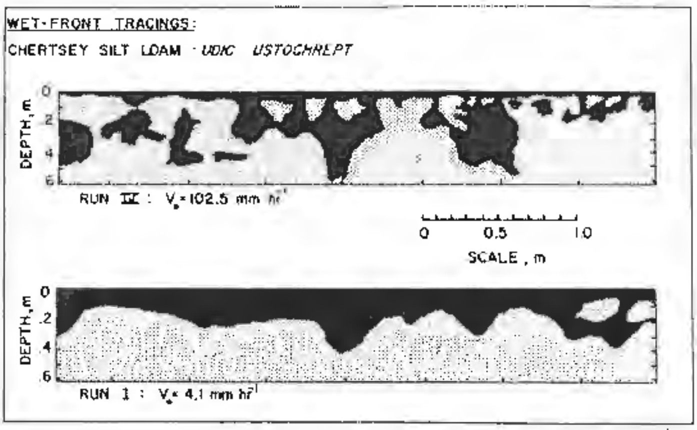

Fig 4.2 The consequences on the uniformity of soil wetting of large-scale runoff under high rates of irrigation (top), relative to that when the rate of irrigation is less than the soil's matrix hydraulic conductivity (from C1-Clothier & Heiler, 1983)

some surface ponding for a time t^* (see Fig 4.1). If the sprinkler rate exceeded K_s, such that $V_o=xK_s$, Clothier found that the fraction of the time that the soil surface would be ponded could be given by,

$$\frac{t^*}{t`}=x-\frac{\left(\frac{(1-\Theta)S^2}{K_s{}^2}\ln\left[1+\frac{2xt`K_s{}^2}{(1-\Theta)S^2}\right]\right)}{2t`} \qquad [4.1]$$

where S is the soil's sorptivity, and $\Theta=\theta_n/\theta_s$ is the ratio of the soil's water content before irrigation to that at saturation.

With Heiler, field experiments were carried out, and calculations from Eq [4.1] showed that when V_o exceeded the K_s of 10.9 mm/hr of the Chertsey silt loam, there would be significant periods of time when the surface would be ponded. Thus local runoff would lead to irregular wetting (Fig 4.1c) that would reduce wetting uniformity, and irrigation efficiency. This was corroborated by observations of the wetting front under two contrasting rates of application (Fig 4.2), and thus cautions against the use of high rates of sprinkler irrigation.

In the book of the proceedings, Curtis Larson summarised the conference and commented on the 36 papers presented. Paper [C1] was, along with one other, considered by Larson to have introduced new concepts in advances in infiltration.

Paper [C2]

At the international conference on "Field-scale Water and Solute Flux in Soils", held at Monte Verità in Switzerland, Clothier presented a invited paper that developed on the ideas of paper [**C1**]. These were corroborated by using Time Domain Reflectometry (TDR) measurements of the soil's water content in the rootzone before, and after irrigation.

Clothier and colleagues showed that measurements of the soil's hydraulic conductivity, made with permeameters of which paper [**A2**] provided the forerunner prototype, could be used to predict the uniform pattern of wetting in the soil surrounding an apple tree, when the rate of sprinkler irrigation was well less that the saturated conductivity (see Fig 4.1 a).

This work has also been frequently cited because the rootzone observations of the field of changing water content, measured by TDR and neutron probing. These revealed an interesting pattern in the apple tree's depthwise flexibility of root uptake. The water extraction observation described in paper [**C2**] stressed the prime role of surface roots in taking up water when the soil profile is uniformly wet. Clothier and colleagues concluded that "... we find the amount of water exiting the rootzone is the result of a complex interaction between the soil's physical properties, and the tree's decision as to where to drink".

Deciphering the tree's depthwise decision-processes became a focus of Clothier's work, and this is discussed further in papers [D2] and [D3].

Paper [C3]
As well as considering sprinkler irrigation, Clothier was interested in the physical factors that control the efficacy of drip irrigation, a common means of irrigating horticultural crops. Here, the irrigation water is simply applied as a series of drips on the soil surface, and it relies on the capillary forces in the soil to work in conjunction with gravity to distribute the water to a large enough proportion of the roots. The role of the soil's hydraulic properties, in relation to the applied dripper rate, Q, is critical.

In paper [C3], Clothier and Scotter showed how two theories could be cobbled together to provide brackets on the behaviour of water flow into soil when water is applied as drips at a point source on the surface. They used Philip and Knight's gravity-free, flux-concentration theory to describe short-time behaviour, and Raats' steady-state solution for longer-times. Clothier and Scotter derived a time-criterion to distinguish between the time zones of applicability. They parameterised these theories using methods described in Chapter 2 of this thesis, and they successfully tested the combined theory in the laboratory using a special sandbox. This was the first experimental test of 3-D theories of infiltration. These data have subsequently used by other researchers for testing new theories, or validating numerical models. As a result, this paper has been cited over 30 times by other scientists, placing it in the top 3% of papers cited by peers (Garfield, 1985 *loc. cit.*).

Paper [C4]
Clothier, in paper [C4], extended the work described above in paper [C3] to develop a means for predicting the movement of solutes away from a dripper, as would happen during the use of 'fertigation' of nutrients with drip irrigation.

From paper [C3], Clothier realised that Raats' steady-state theory had utility at even quite short times, due to the rapid attainment of steady conditions as a result of the 3-D geometry. Raats' theory provides both the pattern of water content away from the dripper, as well as the pore-water velocity field. By combining these two analytical results, Clothier developed an expression for the time of travel away from the dripper along these streamlines. Integration of these travel times down the streamline could then be used to predict the invasion of a solute front into soil around a dripper discharging a chemical. Unfortunately, the complex nature of the integral rendered analytical solution impossible, and Clothier resorted to numerical techniques to find the invasion pattern of chemical. This he tested successfully against solute experiments in his sandbox.

Contemporaneously, John Philip had developed an analytical solution for this. But his analysis had to assume a uniform water content along the streamlines.

Since Clothier had received a prepublication version of Philip's work, he was able to show in paper [C4] the impact of having to assume a constant water content.

As a result of the research developed in papers [C3] and [C4], Clothier has provided practical advice and new ideas, via the popular media (Appendix F), that have helped improve drip irrigation practices. This work has been cited over 22 times by others, placing it in the top 3.5% of papers receiving citations (Garfield, 1985 *loc. cit.*).

Chapter 5

PLANTS, GROUNDWATER PROTECTION AND BIOREMEDIATION OF CONTAMINATED SOIL

Papers cited in this chapter (See Appendix D for reprints)

D1 Green, S.R. and B.E. Clothier, 1988. Water use by kiwifruit vines and apple trees by the heat-pulse technique. *Journal of Experimental Botany* 39: 115-123.

D2 Clothier, B.E. and S.R. Green. 1997. Roots: The big movers of water and chemical in soil. *Soil Science* 162: 534-543.

D3 Clothier, B.E., S.R. Green, B.H. Robinson, T. Thalayakumaran, D.R. Scotter, I Vogeler, T.M. Mills, M. Deurer, M. van der Velde, and Th. Granel, 2002. Contaminants in the rootzone: Biovailability, uptake and transport, and their implications for remediation. Proceedings of the international workshop **"Chemical availability in the terrestrial environment",** Adelaide, 18-20 November 2001 (in press).

As noted in the discussion of paper [**C2**], Clothier and his colleagues had come to realize that a lot of what was going on in the soil of the rootzone was not just due to 'physics'! The role of the plant, via its roots, was often dominant. Yet less effort has been directed to understanding those physical processes that are biogenic, such as the root uptake of water and chemicals. Clothier's research in seeking better observation and clearer understanding of biophysical processes in the rootzone is the subject of this Chapter.

Paper [**D1**]

Whereas it was possible to observe, with ever-increasing detail, the changing pattern of the soil's water content, presumably due to root uptake as shown in paper [**C2**], there was no mass-balance control on what was indeed the total amount of water extracted by the plant. With his colleague, Steve Green, Clothier worked to improve the heat-pulse technique of sap-flow measurement in woody plants, and they carried out rigorous tests of the technique in kiwifruit and apples (Fig 5.1). They found that the unusual vascular structure of kiwifruit, with its large and long xylem vessels, required a reassessment of the 'wound factor' that it used in the compensation technique for measuring sapflow.

With the tools and techniques developed in paper [**D1**], it has become possible to measure routinely and remotely, the water use by trees, so that the amount of plant water extraction from the rootzone is known. As well as kiwifruit and apples, Green and Clothier have applied this technique in New Zealand to poplars, willows, olives,

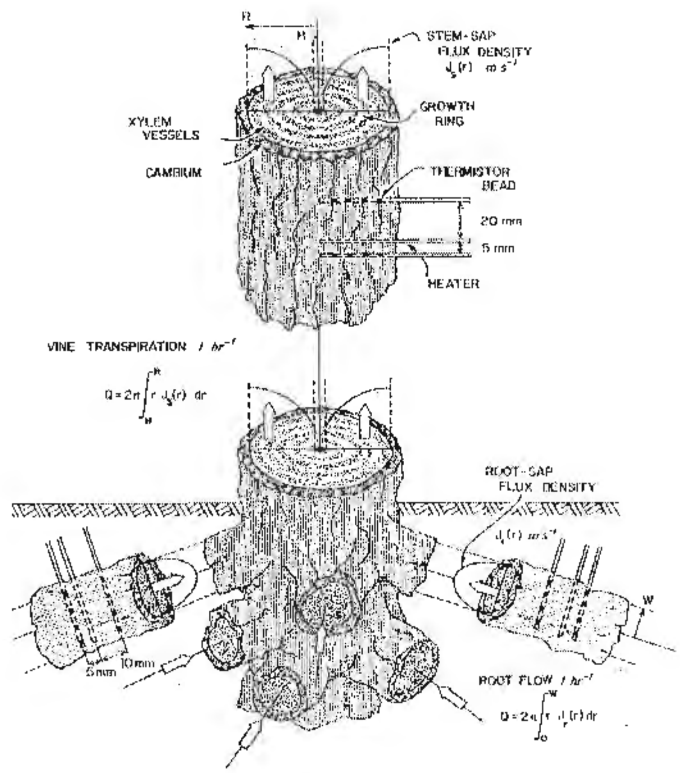

Fig 5.1 The application of heat-pulse technology for measuring sap flow (D1 - Green & Clothier, 1988), as applied to both the stem, and in miniaturised form to roots (from Green & Clothier, 1995, see Appendix F)

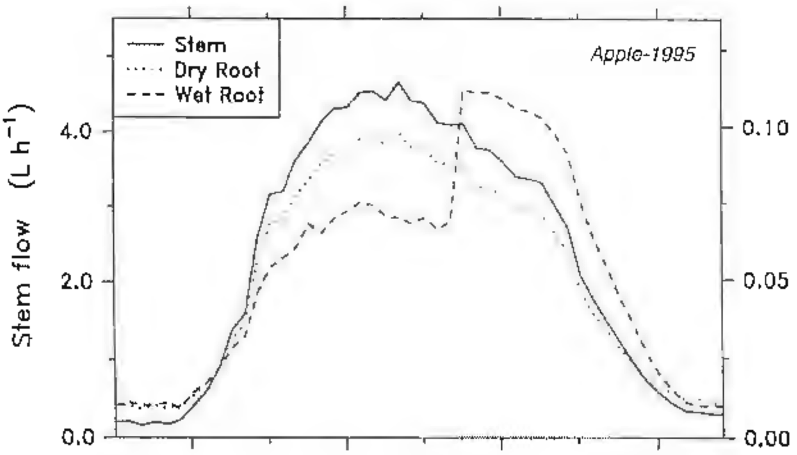

Fig 5.2 The measured surge in sapflow in the wet-root that had been irrigated, in relation to its dry-root neighbour, and the total flow in the stem of the apple. The technology of Fig 5.1 permitted these observations (from D2, Clothier & Green, 1997)

grapes and mandarins. They have also taken this technique to Australia (cashews), Japan (mangoes), Spain (olives), and Italy (grapes).

Paper [**D2**]

Because Clothier and Green's interest was primarily on biophysical processes in the rootzone, rather than micrometeorological exchange-mechanisms, they decided to miniaturise their heat-pulse probes so that they could measure sapflow in large structural roots (Fig 5.1). For the first time, it was possible to observe directly the way in which roots hydraulically behave in relation to the tree's total water use (Fig 5.2). This work is described in paper [**D2**], and in Green and Clothier (1995) in Appendix F.

As shown here in Fig (5.2) (from paper **D2**), with heat-pulse equipment it is possible to observe directly "... the trees decision as to where to drink", something that Clothier has mused about earlier in paper [**C2**]. The so-called 'wet root' of the apple tree in Fig 5.2 was spot irrigated around midday, and an immediate response can be seen in the flow of sap in that root, as the tree moves to increase its reliance on water from that drip irrigated water. This highlights the efficiency of drip irrigation, for the apple has preferentially sought to extract that water, before capillarity and gravity might draw it beyond the roots' grasp, as predicted by papers [**C3**] and [**C4**].

Paper [**D3**]

Clothier entitled paper [**D2**], "Roots: The big movers of water and chemicals in soil". That they are, is the key mechanism in the burgeoning use of plants, and other soil biota, for remediating contaminated soils. This process, called phytoremediation, has become a focus of recent endeavours by Clothier and his team. In a recent review of phytoremediation by an American engineer, it was cautioned "... this technology is not simply the buying of plants from the local K-mart and placing in the soil near a contaminated site!" Clothier concurs.

In paper [**D3**], Clothier detailed the efforts of his team to decipher the mechanisms that control the bioavailability, transport and plant uptake of both metals and organic contaminants in soil, and he discussed their implication for phytoremediation of contaminated sites. In Fig (4) of paper [**D3**], it is shown that when poplars are grown on soil containing 20 ppm of boron (B), their leaves can accumulate up to nearly 800 ppm B, making them prime candidates to clean-up B-contaminated sites. However, via large lysimeter experiments, it was shown that the uptake efficiency of B from the soil solution was only about 10% (Fig 5 in **D3**), such that the B-levels in any leachate could still pose an offsite threat, even though the trees can extract significant amounts of B. Thus when planning to phytoremediate contaminated sites, it is imperative that cognizance be taken of the hydraulic processes operating in the rootzone, as described in Chapter 2 of this thesis. In their practical application of this phytoremediation technology, Clothier and team are recycling the leachate (Fig 2 of **D3**) to limit offsite deleterious impacts.

Chapter 6

INVITED REVIEWS, INTERNATIONAL ADDRESSES AWARDS AND HONOURS, EDITORIAL AND ACADEMIC PERFORMANCE, IMPACT

Papers cited in this chapter (See Appendix E for reprints)

E1 Clothier, B.E. 2002 Rapid and far-reaching transport through structured soils: A commentary. *Hydrological Processes* (in press)

E2 Clothier, B.E., I. Vogeler, S.R. Green and D.R. Scotter. 1998. Transport in unsaturated soil: Aggregates, Macropores, and Exchange. In *Physical Nonequilibrium in soils: Modeling and application* [H.M. Selim & L. Ma, eds], Ann Arbor Press, Chapter 10:273-294.

E3 Clothier, B.E. and S.R. Green. 1994. Rootzone processes and the efficient use of irrigation water. (Review Article) *Agricultural Water Management* 25:1-12

E4 Clothier, B.E., S.R. Green, I. Vogeler, B.H. Robinson, T.M. Mills, C. Duwig, J. F. Roygard, M. Walter, C. W. van den Dijssel, and D.R. Scotter. 2000 Contaminants in the soil environment: Transport, uptake and remediation. Plenary Address, *In* "Contaminants in the soil environment in the Australasia-Pacific region", New Delhi, 12-17 Dec, 1999

Invited Reviews

As well as being tactically involved in biophysical research of rootzone processes, Clothier has also developed a keen strategic overview of the state-of-the-science. Consequently he has been invited to write many reviews. Here in Chapter 6, four reviews are discussed, and each relates respectively to the work carried out in Chapters 2 to 5. Other reviews and book chapters can be found in Clothier's bibliography (Appendix F).

Paper [**E1**]

There is still a continuing interest in better understanding, and predicting the consequences of the rapid and far-reaching transport that occurs through soils riddled with macropores (Chapter 2). In 2001, Clothier was invited to present a keynote address on this topic to a Chapman Conference sponsored by the American Geophysical Union. Following that address, Clothier was asked to prepare a critical commentary for the journal *Hydrological Processes*. This commentary is presented here as paper [**E1**]. Clothier feels that is we are to advance our understanding of the ubiquitous phenomenon of rapid and far-reaching transport in macroporous soil, we will need to leave behind many of our traditional concepts. However, he concluded that better observation from new tools, which can be analysed using novel analytical schemes, will advance our understanding of macropore flow.

Paper [E2]

In a review of the transport of chemicals through soil (paper [**E2**]), Clothier noted that we have significantly advanced our understanding of how both inert and reactive solutes move through structured porous media. However, Clothier showed in paper [**E2**] that there is still difficulty in unequivocally resolving, using such inverse procedures as discussed in Chapter 3, the parameters that purport to describe the transport and exchange mechanisms. He repeated Fourier's lament that "Nature is indifferent to the difficulties it causes mathematicians". Nonetheless, Clothier concluded that new devices are providing us with vision of greater acuity concerning the role that aggregates and macropores play in controlling chemical transport through unsaturated soil.

Paper [E3]

To mark publication of the 25th volume of the international journal *Agricultural Water Management*, Clothier, its Joint Editor-in Chief, was asked to write a review on "Rootzone processes and the efficient use of irrigation water". This is paper [**E3**], and his views derive from the research discussed in Chapter 4 of this thesis.

In paper [**E3**], Clothier discussed the better matching of irrigation devices to the soil's hydraulic character, and the incorporation of new knowledge about water extraction by roots into irrigation scheduling practices. He concluded that new technology and knowledge will continue to change irrigation practices to make better use of precious water resources.

Paper [E4]

The second international conference on "Contaminants in the Soil Environment in the Australiasia-Pacific Region" was held in late 1999 in New Delhi. Clothier was invited to be the Plenary Speaker at this meeting and he chose to talk on "Contaminants in the soil of the rootzone: Transport, uptake and remediation". This is included here as paper [**E4**], which reviews research described in Chapter 5.

Clothier considered that better protection of the soil environment, and improved health of our water resources will arise through new knowledge of those biophysical processes governing the transport, uptake and exchange of chemicals in the rootzone. New measurement techniques, in tandem with the use of soundly-based mechanistic models, will assist the quest for land management strategies that afford environmental protection, as well as effective procedures that can remediate contaminated sites.

International Addresses

Clothier has received many invitations to present keynote addresses, or be a plenary speaker. Full details can be found in his *curriculum vitae* in Appendix F, but some of the major addresses are listed below. These include:

- Symposium speaker, International Soil Science Society XIII Congress, Hamburg, Germany, August 1986
- Plenary Speaker, Irrigation Speciality Conference, American Society of Civil Engineers, Portland, Oregon, July, 1987
- Invited address, International Symposium on Water Quality Modeling of Agricultural Non-point Sources, USDA, Logan, Utah, June 1988
- Symposium speaker, International Soil Science Society XV Congress, Acapulco, Mexico, July 1994
- Distinguished Lecturer, The Waite Institute, University of Adelaide, Australia, July, 1995
- Invited address, International Workshop on "Advances in Soil Science", University São Paulo, Brazil, October 1999
- Plenary Speaker, The Kirkham 2000 Conference, Ames, Iowa, November 2000
- Invited Speaker, Chapman Conference on "State-of-the-Art in Hillslope Hydrology", American Geophysical Union, Sunriver, Oregon, October 2001
- Keynote Speaker, International Workshop on "Chemical Bioavailability in the Terrestrial Environment", November 2001, Adelaide, Australia
- Keynote Speaker, DOE Workshop "Earth System Questions for Climate Change Science", Biosphere 2, Oracle Arizona, December 2001.

Awards and Honours

A full listing of the awards and honours that Clothier has received can be found in his *curriculum vitae* which is included in the thesis as Appendix F. A summary of the significant awards is just presented here.

- Fellow, **Royal Society of New Zealand** (elected 1994)
- Fellow, **Soil Science Society of America** (elected 1992)
- Fellow, **American Society of Agronomy** (elected 1995)
- Fellow, **New Zealand Society of Soil Science** (elected 1995)
- The 2000 Don and Betty Kirkham Soil Physics Award, **Soil Science Society of America**
- The 2001 J.A. Prescott Medal, Outstanding contribution to soil science **Australian Society of Soil Science Inc.**
- The M.L. Leamy Award, Most meritorious NZ contribution to soil science 1990-92, **New Zealand Society of Soil Science**
- The Norman Taylor Lecturer, **New Zealand Society of Soil Science**, 1995
- Best Oral Presentation, Australia & New Zealand Soil Science Conference, July 1996, Melbourne, Australia
- Visiting Fellow, **Japanese Society for the Promotion of Science**, Kyoto University, 1997

Editorial and Academic Performance

Clothier is committed to the publication process of science. He is:

- o *Joint Editor-in-Chief* of the international journal "**Agricultural Water Management**", Elsevier, Amsterdam, The Netherlands. (Appointed 1996, Associate Editor 1992, Board member since 1985)

- o *Senior Editorial Board member* (responsible for physics) of the international journal "**Plant and Soil**", Kluwer, Dordtrecht, The Netherlands. (appointed 1992, Board member since 1986)

- o *Chair, Editorial Advisory Board member* of the international journal "**Australian Journal of Soil Research**", CSIRO Publishing, Melbourne, Australia.

- o *Member, Board of Standards*, CSIRO Publishing, Melbourne, Australia

- o *Editorial Board member* of the international journal "**Journal of Contaminant Hydrology**", Elsevier, Amsterdam, The Netherlands.

- o *Editorial Board member* of the international journal "**Soil & Tillage Research**", Elsevier, Amsterdam, The Netherlands

- o *Co-founder and Current Editor*, "**WISPAS**", a scientific newsletter about water research into soil-plant-atmosphere system. **WISPAS** is published 3 times a year, and was founded in 1974.

As well, Clothier is committed to capacity development through supervision of post-graduate students, and examination of their theses. Since 1983, Clothier has successfully co-supervised 15 post-graduate students. He is currently the co-supervisor of three PhD students, including one from the Catholic University of Louvain in Belgium. In the last 15 years, Clothier has examined 22 post-graduate theses. This includes theses from 5 Universtities in New Zealand, and 2 in Australia. Because of his fluency in French, Clothier has been a member of the examination jury on 12 theses from 3 Universities in France.

Impact

A keen assessment of the impact of Clothier's scientific endeavours can be made through a quantitative analysis of the citations made to Clothier's work by his colleagues and peers. Over the last 27 years, Clothier has been the author, or co-author of 129 refereed publications, and of these he was the senior author on 53 papers. These 53 publications have yielded, according to the Institute for Scientific Information, over 657 citations. This represents, on average, a high impact rate of 12.4 citations per paper. Only some 9% of cited papers ever receive more than this number of citations (Garfield, 1985 *loc. cit.*)

Yet, more importantly, 3 of Clothier's publications have been cited over 50 times. These are papers [A2], [B2], and paper 27 in Appendix F. Only 1.1% of cited papers ever exceed this level of impact (Garfield, 1985 *loc. cit.*).

Clothier's most significant *oeuvre* is paper [A2], which has, since 1981, been cited over 142 times. This high impact paper is therefore in the top 0.33% of cited papers (Garfield, 1985 *loc. cit.*).

Thus, Clothier's scientific career has not only produced significant results across the gamut of research into the behaviour of water and solutes in soil, but he has also created new understanding in the key areas of hydraulic characterisation, sustainable production, and environmental protection.

***Publications: Book Chapters* (16), *Scientific Publications* (113), *& Articles* (97)**

Book Chapters

1. McNaughton, K.G., B.E. Clothier, and J.P. Kerr, 1979. Evaporation from land surfaces. In "*Physical Hydrology: New Zealand Experiences*" pp 97-119, published by the N.Z. Hydrological Society.

2. White, I., B.E. Clothier and D.E. Smiles, 1982. Pre-ponding constant rainfall infiltration. In "*Modeling components of hydrologic cycle*", published by Water Resources Publications, Colorado, U.S.A., pp. 127-148.

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11. Vogeler, I., S.R. Green, B.E. Clothier, M.B. Kirkham and B.H. Robinson, 2001 Contaminant transport in the root zone. **In** "*Bioavailability, fluxes and transfer of Trace Elements in Soils and Soil Components*" (I.K. Iskandar & M.B. Kirkham, Eds) Lewis Publishers (CRC Press), Chap 9:175-198.

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13. Fernández, J.E., B.E. Clothier, and M. van Noordwijk 2000. Water Uptake. In *Root Methods: A Handbook* ,A.L. Smit *et al.* (eds), Springer-Verlag, Berlin Heidleberg, pp 461-508.

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16. Clothier, B.E. 2002. Bioavailability: A conspectus. Proceedings of the international workshop **"Chemical availability in the terrestrial environment",** Adelaide, 18-20 November 2001 (in press)

Scientific Publications

1 Greenland, D.E. and B.E. Clothier, 1975. A study of radiation in the New Zealand Southern Alps. *Geografiska Annaler* 57A: 143-151.

2 Clothier, B.E., D.R. Scotter and J.P. Kerr, 1977. Water retention in soil underlain by a coarse-textured layer: Theory and a field application. *Soil Science* 123: 392-399.

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