PEDO-TRANSFER FUNCTIONS FROM S-MAP FOR MAPPING WATER HOLDING CAPACITY, SOIL-WATER DEMAND, NUTRIENT LEACHING VULNERABILITY AND SOIL SERVICES

Linda Lilburne[1*], Trevor Webb[1], Dave Palmer[2], Stephen McNeill[1], Allan Hewitt[1] and Scott Fraser[2]

[1]*Landcare Research, PO Box 69040, Lincoln 7640, New Zealand*
[2]*Landcare Research, Private Bag 3127, Hamilton 3240, New Zealand*
**Email: lilburnel@landcareresearch.co.nz*

Abstract

Recent modelling developments within S-map (New Zealand's soil survey data information system) have been designed to support nutrient management at multiple scales. A suite of models has been developed, implemented and tested. These are characterised as soil-only pedo-transfer functions (ptf), soil–climate models, and soil–climate–land management models. The suite of models has a range of uses, from estimating hard-to-measure soil properties used in paddock- or farm-scale agricultural models to estimating water demand and nutrient loads at the catchment or regional scale.

Introduction

Demand for accessible, comprehensive, and quantitative soil information to support sustainable management led to the design and implementation of a new national soil information system, S-map. One of the initial drivers for S-map was the need for quality-input soil data to support environmental and production models needed by land-based industries and policy agencies (Lilburne *et al*. 2012). Generation of the full suite of desired soil data inputs requires development of pedo-transfer functions (ptfs) to predict soil properties that are expensive or difficult to measure. These ptfs sit in the inference engine component of the S-map Information System (Figure 1). They are codified algorithms derived from statistical and mechanistic modelling or expert knowledge. These algorithms draw upon underlying core S-map data and analytical laboratory data stored in the National Soils Database (NSD) (Wilde 2003). Data outputs from the ptfs and the core S-map data all form part of S-map and are delivered to end-users through a variety of means including web portals and services (Figure 1). Core and derived soil properties from S-map can also be combined with other datasets (e.g. climate, geology, land use, topography) in models to predict a range of information relevant to resource management.

This paper reports on a specific set of S-map ptfs and models, designed to support nutrient management at multiple scales, that have been developed, implemented and tested. The ptfs include a statistical analysis of analytical measurements of soil water retention held in the NSD, resulting in S-map ptfs for water content at field capacity and wilting point, and profile available water (PAW). Ptfs describing soil-related vulnerabilities to nutrient leaching, runoff, and bypass flow were also developed. The output of these ptfs can then be used in a variety of contexts, either directly within S-map, for example on the soil fact sheets, or in other applications, for example the nitrate leaching vulnerability model can be recast in terms of soil ecosystem services, in this case as the 'regulation of N filtering and N reduction' services.

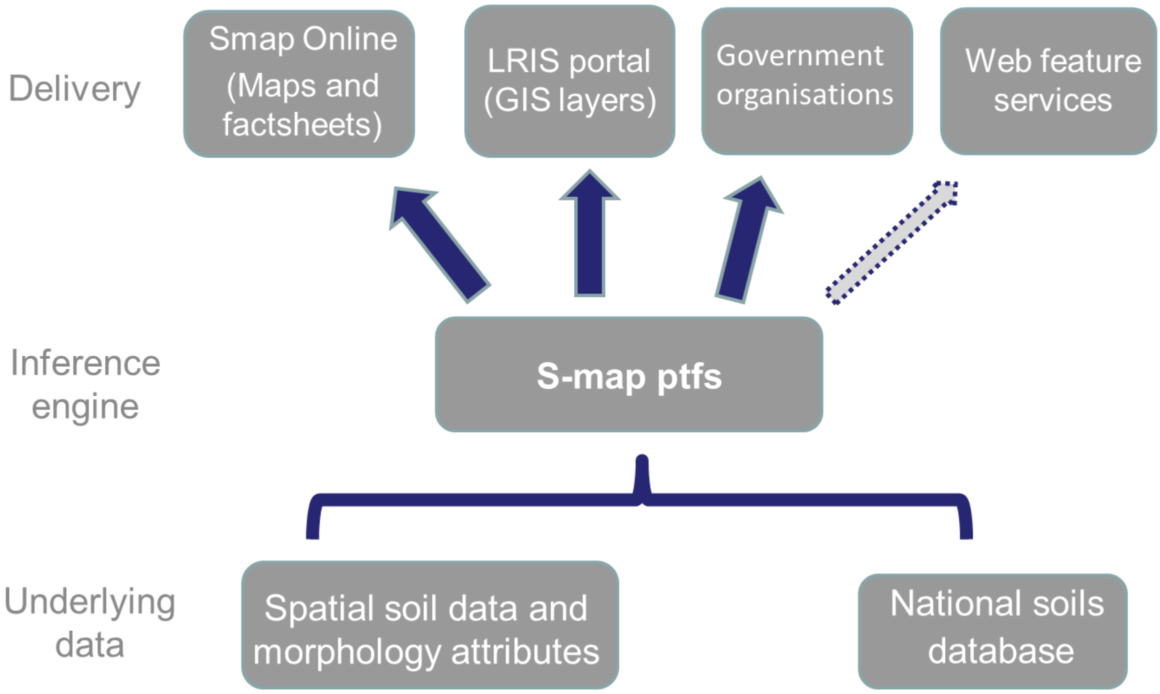

Figure 1 The S-map Information System.

These soil-based models can be extended to account for spatial variation in rainfall and potential evapotranspiration, by running a daily water balance for each soil to estimate annual accumulated drainage; thus creating a spatial layer of leaching vulnerability based on soil and climate. Another output of this soil–climate modelling is 'water demand', which can assist investigating the development of new irrigation schemes. Finally, information about land management (i.e. nutrient inputs) can be combined with the vulnerability ptfs to estimate nitrate leached under different land management scenarios.

Soil-based ptfs

Water retention curve ptfs

The water retention curve (WRC) is modelled using a regression model based on soil order, parent rock, soil functional horizon information (stone content, soil density class), as well as texture (field estimates of sand, silt and clay percentages). The water content value (in percent) at 1500 kPa tension (wilting point) is predicted directly from a regression model (Figure 2). The water content at a tension of 100 kPa is then predicted using the estimated value for a tension of 1500 kPa, plus the modelled difference of the water content values between 1500 and 100 kPa, which is always positive. The water content at each of four other tension values (5, 10, 20, or 40 kPa) is predicted in a similar manner. In this way, the modelled water content closely matches the observed water content values in the NSD, and the predicted WRC values for different tensions respect the observed differences between WRC values at different tensions from the NSD data.

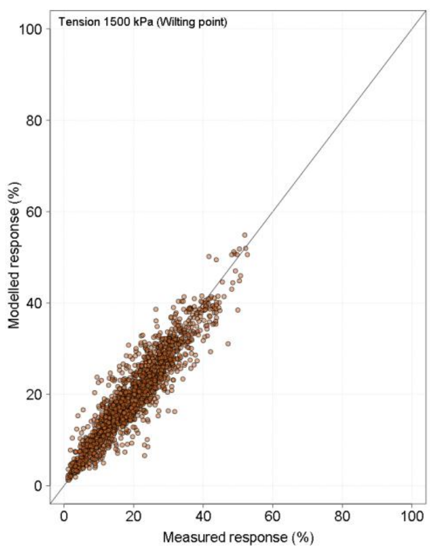

Figure 2 Predictions of water content at wilting point compared to measured values.

Vulnerability ptfs

Vulnerability impacting on water quality considers the inherent attributes of the land that determine the susceptibility of soils to transport contaminants through the soil profile (as leaching) or over the soil surface (as runoff) to where these may enter either groundwater or surface water bodies. Four soil vulnerability ptfs have been implemented within the S-map inference engine that describe the likelihood of leaching nitrogen and phosphorus, runoff enriched by phosphorus (and sediment) , and the transportation of contaminants more rapidly via bypass flow, all described by Webb *et al*. (2010). The analysis does not quantify vulnerability but provides a relative ranking of land on a national scale from most vulnerable to least vulnerable. Each of these ptfs is based on relevant soil properties. For example, nitrate leaching vulnerability relates to the profile available water of the soil and the likelihood of denitrification, whereas phosphorus leaching vulnerability (Figure 3) is linked to the soil's phosphorus adsorption capacity.

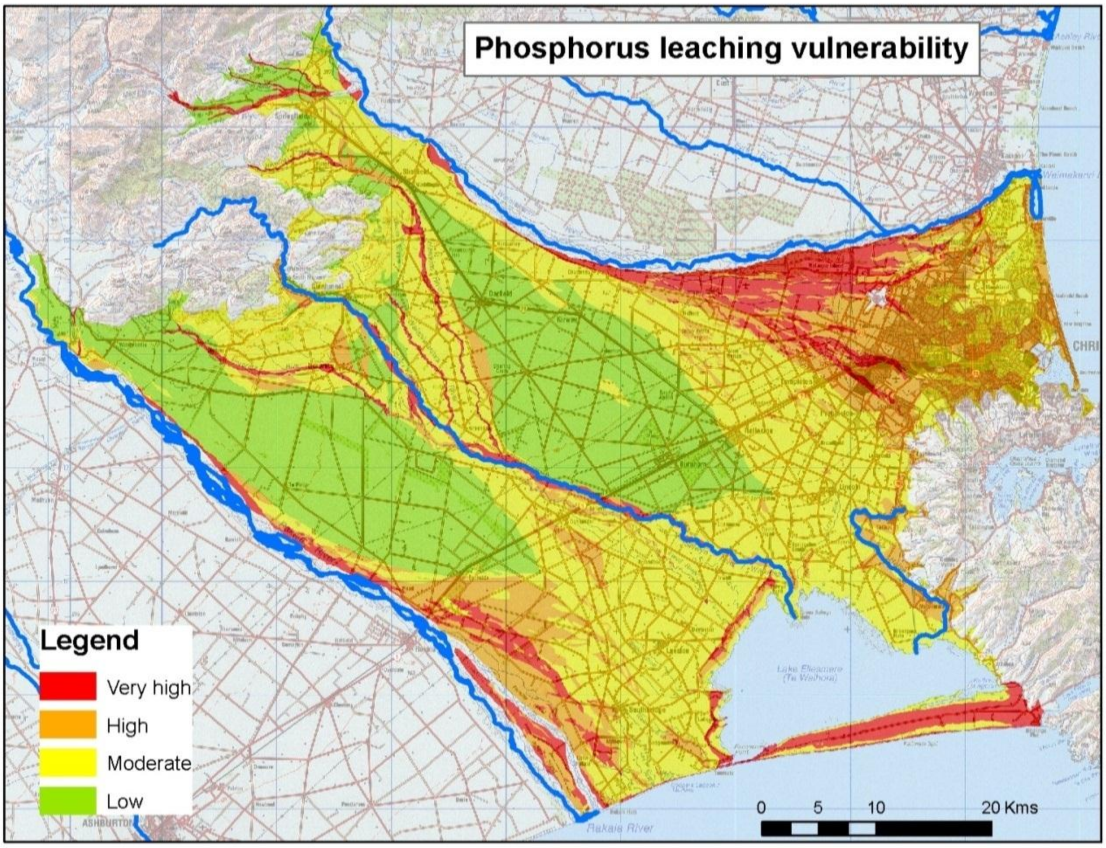

Figure 3 Phosphorus leaching vulnerability for the central plains of Canterbury.

The vulnerability to bypass flow ptf extends the work of McLeod *et al*. (2005, 2008). This research modelled potential microbial bypass flow for New Zealand soils by ranking soils into high, moderate and low classes on the basis of insights gained from microbial breakthrough curves and relating these to soil classification and soil characteristics.

The relative vulnerability of land to runoff provides an index of the potential for fine particulate matter, including microbes, aggregates of microbial matter, soil organic matter, P particles (either fertiliser materials or sediment particles with attached P), or fine sediment to be carried by runoff flow into surface water bodies. The relative runoff potential is based on the relative capacity of different soils to infiltrate rainfall when the soil is at field capacity (Farquharson *et al*. 1978). This is related to the capacity of soil for rainfall to infiltrate until the point when the rate of infiltration is governed by the horizon with the slowest permeability. It is estimated in S-map by the permeability and macroporosity of subsurface layers above the slowly permeable layer (if any). Macroporosity is a measure of the soil's initial capacity for rainfall to infiltrate into air-filled pores. The permeability of subsoil horizons governs the longer-term rate of infiltration.

Ecosystem service ptfs

Soil natural capital (SNC) is defined as the capacity of the soil to support the soil services required by a specified land use, where sustainable land management practices are assumed (adapted from Dominati *et al*. (2010)). SNC is a natural asset and the soil profile (pedon) is regarded as the basic unit of this asset. The soil profile is interpreted as comprising a bundle of soil stocks. Soil stocks are the soil properties that drive the soil processes that are recognised as either soil functions or soil ecosystem services.

For effective operation these services need to draw upon a specific set of soil stocks. If these stocks are adequate then the soil services can operate to their full potential, and in turn, the land use type can operate to its potential. If the soil stocks are not adequate then the soil services, and in turn the land-use type, will have limited productive output or limited ability to mitigate environmental risks.

N-leaching vulnerability, as applied above, includes two components: (1) N storage in various forms in soil solution within soil pores from which it is extracted by plant roots, and (2) biological reduction of nitrate under reducing conditions, with evolution of gaseous forms of nitrogen including N_2 and nitrous oxide to the atmosphere. An S-map ptf has been developed that maps the N-leaching adequacy combining both the nitrate-filtering and nitrate-reducing services. These two components can also be separated into two soil services: N filtering, and N reduction.

Soil–climate models

Nitrate leaching vulnerability model

The simple qualitative nitrate leaching vulnerability ptf of the previous section has been developed into an index of nitrate leaching by the inclusion of climate variables. This nitrate leaching vulnerability index has been applied to a map of dairy and dairy support land in the upper Waikato River catchment (between Karapiro Dam and Huka Falls). In this case nitrate leaching vulnerability is based on profile drainage calculated using profile available water (PAW) from S-map, climate data from NIWA, and a daily soil water balance model (Fraser *et al*. 2013).

The climate property used in soil–water balance modelling with the greatest sensitivity to change in temporal trends is precipitation. Rudimentary soil-water-balance models often distribute rainfall (monthly daily averages) evenly across each day in a month. This effectively constrains the model simulation, impacting on drainage rates and the natural daily variability that occurs. To improve model simulations, 365 rainfall surfaces were created using the protocol of Palmer *et al*. (2009). Two datasets were used to create daily rainfall for the southern Waikato region: NIWA's monthly mean rainfall surfaces (500-m cell size resolution), and Virtual Climate Data (VCD) (point data modelled at a 5-km resolution). The criteria used to select months representing 'normal' rainfall distributions across each month from the ~40 years of VCD were:

1) Months closest to average number of rain days, and
2) Months closest to the mean monthly sum of rainfall.

The final 365 rainfall surfaces were developed by allocating the VCD daily rainfall pattern across each month to the long-term monthly mean rainfall surfaces at a 200-m cell size resolution. The outcome of this was 365 surfaces representing daily rainfall based on long-term climate data.

NIWA's long-term monthly estimates of potential evapotranspiration (PET), developed from the Priestley–Taylor method, were apportioned equally across each month on a daily basis.

The output from the daily water balance calculation is an annual accumulative drainage surface in millimetres that was then attenuated according to a factor related to biochemical soil reduction as indicated by poor soil drainage or the presence of organic soil materials. The attenuated drainage was classified into five nitrate leaching vulnerability classes.

Irrigation water demand modelling
In a similar study of soil–water balance, using S-map soil data and VCD data from the Wairarapa, the water deficit was calculated under a median rainfall year and the 10th percentile rainfall year. Irrigation water demand was adjusted to account for the effect of capillary flow from groundwater. For land parcels that had consented volumes of irrigation water, the irrigation was then applied according to demand (set at when 50% of the soils' water holding capacity was reached) to give irrigated water demand surfaces for the median (Figure 4) and 10th percentile rainfall years.

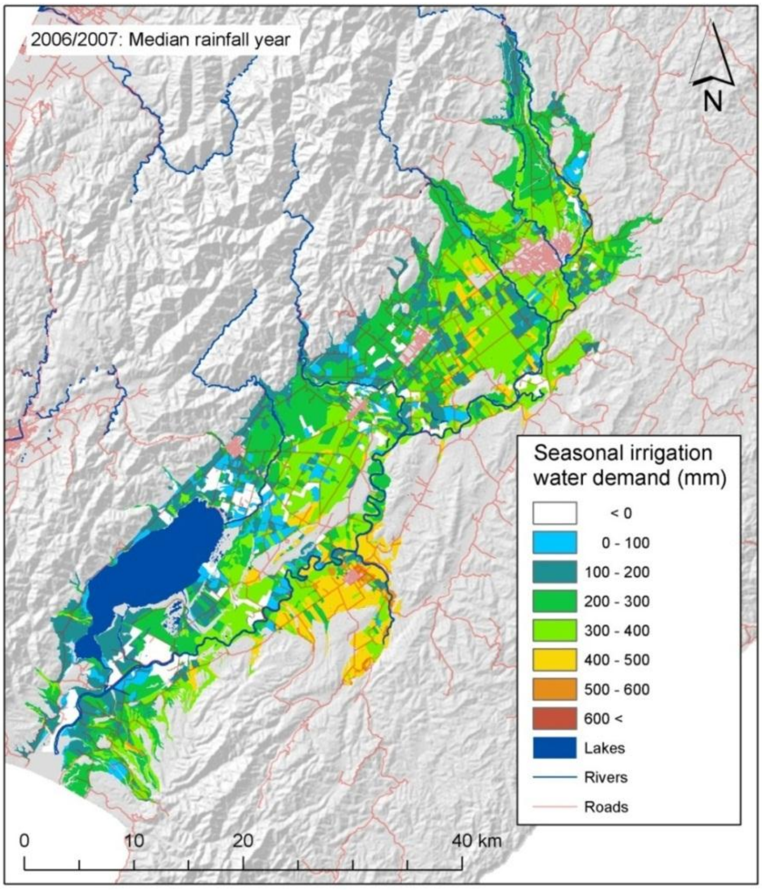

Figure 4 Water demand across the irrigation season (October–March) for the median rainfall year with consented volume accounted for.

Soil–climate–land management models
The soil-based vulnerability ptfs and soil–climate models described above indicate relative risk of pollution if the same management practices are carried out on all landscapes. The resulting maps depict vulnerability rather than risk. Risk expresses the interaction of the inherent vulnerability of the land together with land-use pressure and the likely consequences for receiving water bodies. Land-use pressure will vary according to land management practices.

Land use information (Agribase 2011) and nutrient modelling results recorded in lookup tables (Lilburne et al. 2010, 2013), soil and rainfall layers were combined to produce maps of nutrient loads under current land use and a set of land use scenarios (Robson 2014). This spatial information was then passed to experts on groundwater and surface water quality for determining the likely environmental impacts of the estimated nutrient loads.

Discussion and Conclusion
The suite of ptfs or models within S-map has a range of uses, for example estimating the effects of land use practices and land-use-change scenarios, and to indicate vulnerable landscapes where mitigation practices are of greatest importance. Soil-water characteristics and other pedological information from S-map can be entered into nutrient budget models (e.g. OVERSEER®[1]), mechanistic nutrient leaching models (e.g. APSIM[1] and SPASMO[1]), irrigation models (e.g. IRRICALC[1]), effluent management systems (e.g. dairy effluent storage calculator[1]), all for use at the farm scale. On land with high soil variability more detailed soil survey may be required, that can then be linked to the S-map ptfs, providing cost-effective soil information for farm-scale management decisions (Carrick *et al*. 2014).

The soil- and soil–climate-based vulnerability models are useful for district- and regional-scale analyses where education or regulation is needed to limit the potential for significant nutrient losses, or conversely to support the design of new irrigation schemes to maximise water and nutrient use efficiency. The soil–climate–land management models are used to predict catchment nutrient loads – an essential step in setting water quality objectives. These models have been used to help communities understand the likely impacts of possible land use changes, irrigation developments, and policy constraints on water quality (Robson 2014).

The water retention and water holding capacity ptfs are a key component of all of the models described above. It is important therefore to consider the accuracy of these ptfs, which are based on analytical data from the NSD. While the impact of this uncertainty will be fully analysed in another project, a preliminary analysis found higher-than-expected values for field capacity for Pumice soils, indicating a need for improved analytical data in the NSD for Pumice soils linked to actual field measurement of water dynamics for these soils.

The ongoing derivation of soil property ptfs from statistical modelling of analytical data from the NSD linked to S-map also highlights the importance of extending the range of data that are currently in the NSD. There is a lot of publicly-funded analytical information that is not currently stored in the NSD. Including these data in any statistical analyses is likely to significantly improve the estimates of derived soil properties.

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[1] OVERSEER® (www.overseer.org.nz/), APSIM (http://www.apsim.info/),
SPASMO (http://tools.envirolink.govt.nz/dsss/soil-plant-atmosphere-system-model/),
IRRICALC (http://www.irrigationnz.co.nz/irrigators/water-allocation/irricalc-central-canterbury/),
Dairy effluent storage calculator
(http://www.dairynz.co.nz/page/pageid/2145878436/Dairy_effluent_storage_calculator_6-15_).

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