Modelling wetland extent using terrain indices, Lake Taupo, NZ

McKergow L. A. [1], J. C. Gallant[2] and T. I. Dowling[2]

[1] NIWA, PO Box 11115, Hamilton, 3251, New Zealand
[2]CSIRO Land and Water, GPO Box 1666, Canberra, ACT 2601, Australia
Email: l.mckergow@niwa.co.nz

Keywords: *Wetland, terrain indices, MRVBF, FLAG, Lake Taupo*

EXTENDED ABSTRACT

While the importance of large wetlands is well recognised and they are easily identified, the same cannot be said for small wetlands. Individually small wetlands may seem insignificant, but collectively they could play an important role in moderating flows and improving water quality in agricultural catchments. Ground-based surveys of small wetlands are time consuming while analysis of aerial photographs and satellite images is affected by trees. The use of terrain analysis to predict “potential” wetlands has the advantage of being systematic and avoids problems caused by trees. We explore the potential of terrain indices for identifying the extent of wetlands in the small agricultural Tutaeuaua catchment (6.6 km^2) which drains to the north western shore of Lake Taupo, New Zealand.

Three terrain indices were used to predict possible wetland locations – topographic wetness index, MRVBF and FLAG. The topographic wetness index (TWI=ln(A_s/tan β)) predicts that sites lower in the catchment are the wettest. The MRVBF (multi-resolution valley bottom flatness; Gallant and Dowling, 2003) index identifies valley bottoms by combining flatness (inverse of slope) with lowness (relative to a circular surrounding area) at a range of scales. FLAG (fuzzy landscape analysis GIS; Roberts et al., 1997) combines two normalised indices calculated from elevation to give locations in the local landscape that are low and have high contributing areas. A filled 10 m DEM and ArcInfo 8.1 were used for the modelling. Evaluation included visual assessments of patterns and areas of prediction, and cell by cell comparisons of predicted wetlands with ground truth data. For ground-truthing, a geo-botanical survey of wetlands in the catchment was undertaken using a mobile GIS.

Over 5% of the farmed catchment area in the Tutaeuaua is wetland. There are a mix of riparian and seepage wetlands, with larger wetlands generally in the headwaters and smaller seepage wetlands in narrow steep-sided valleys. The spatial pattern of potential wetlands predicted by FLAG generally agrees with the mapped wetlands, particularly the larger valley bottom wetlands. TWI delineates the stream network well, but under-predicts the wetland widths, particularly for the larger wetlands. The areas with MRVBF values over 2.5 generally fall within the area identified as wetlands. MRVBF overestimates the area of wetlands by identifying flat areas distant from the stream network as potential wetland.

The terrain index FLAG presented in this study offers a useful technique for identifying the locations and areal extent of valley bottom wetlands in agricultural landscapes. The transferability of this method for predicting wetland location and extent to catchments with different physiography remains to be tested.

1. INTRODUCTION

The volume of water that passes through wetlands at a regional or landscape scale is largely unknown. Wetlands are often studied at the local scale, rather than the regional scale. In addition large wetlands are typically known, but the spatial distribution of small wetlands is not well known understood (Merot et al., 2003). Small wetlands may individually play a small role in moderating catchment flows and water quality, but collectively, at the catchment scale, they may be important. Dowling et al. (2003) drew similar conclusions about the significance of small storage areas for salinity.

Awareness of the functional role of headwater wetlands is increasing, in parallel with their disappearance in agricultural systems (Merot et al., 2006). Small wetlands are likely to be seepages, which tend to occur on moderate to steep hillslopes and at the heads and sides of small streams. They are predominantly groundwater fed with moderate flow rates (Johnson and Gerbeaux, 2004). These small wetlands are typically grazed by livestock, particularly where wetland soil depths are shallow. Elevated exports of *E. coli* have been recorded during flow events (Collins, 2004) and organic nitrogen exports are elevated when stock graze these small wetlands (McKergow et al., 2007).

A first step in managing small wetlands to exploit their potential to moderate water flow and quality in agricultural catchments is identification. A catchment with 20% of its area in wetlands will require a different management strategy to one that is only 2% wetland.

Ground-based surveys of small wetlands are time consuming while analysis of aerial photographs and satellite images is affected by trees. The use of terrain analysis to predict "potential" wetlands has the advantage of being systematic and avoids problems caused by trees. Wetlands have been successfully identified using topographic wetness indices in small catchments (<48 km^2) in Europe, with more success in hilly to mountainous landscapes than low relief (Rodhe and Siebert, 1999; Merot et al., 2003). Merot et al. (2003) tested topographic indices in small catchments in six European countries and found that the general wetland form was identified (e.g. round Polish mires and patches of variable width in France), but precise positions were not.

The assumption underlying topographic analysis in hydrological applications is that topographic attributes are a good surrogate for soil wetness and flowpaths. This assumption may not hold in parts or all of some catchments. While it may hold true for upland areas, the bedrock topography may be a more important than surface topography for controlling the movement of water laterally downslope (McDonnell, 2003). For example, Rodhe and Siebert (1999) suggest that geology is an important control on wetlands in the Nästen catchment, where groundwater is dammed by bedrock.

Data resolution can be a problem with both satellite imagery and terrain indices. The typical length of topographic features (e.g. valley bottoms) may be less than typical grid resolutions (may range from 20 to 50 m; Gunter et al., 2004; Rodhe and Siebert, 1999). In river locations, Merot et al. (2003) found that the similarity between pixel size and wetland features was a problem. When a good quality, high resolution DEM is available, topographic indices could be a suitable method for mapping riverine and palustrine wetlands under both forest and pasture land cover.

In this paper, we explore alternative terrain indices for identifying the extent of wetlands in the small agricultural Tutaeuaua catchment (6.6 km^2) which drains to the north western shore of Lake Taupo, New Zealand.

1.1. Terrain indices

The most commonly used topographic wetness index is $W = \ln (A / \tan \beta)$, where A is the specific catchment area ($m^2\ m^{-1}$) and β is the slope gradient (in degrees). This predicts that points lower in the catchment are the wettest, and soil water content decreases as the flowlines are traced upslope to the catchment divide (Wilson and Gallant, 2000). However, W uses a surface defined upslope contributing area and some landscape features may not depend on surface conditions (Summerell et al., 2004). Two alternative conceptual models were trialled, MRVBF (Gallant and Dowling, 2003) and FLAG (Roberts et al., 1997; Summerell et al., 2004).

The MRVBF index identifies valley bottoms by combining flatness (inverse of slope) with lowness (relative to a circular surrounding area). The assumptions behind the index are: (1) valley bottoms are low and flat relative to their surroundings, (2) valley bottoms occur at a range of scales, (3) large valley bottoms are flatter than smaller ones. The analysis is carried out independently at a range of scales, which enables broad-scale and finer scale features to be identified. The DEM cell size increases by a factor of 3 and the slope threshold decreases by a factor of 2 for each step. A location is considered to have valley bottom flatness at a given scale if it is sufficiently low and flat at that scale and is sufficiently flat (but not necessarily low) at all finer scales (Gallant and Dowling, 2003). While MRVBF is a continuous measure, classes can be identified: values less than 0.5 are not valley bottom areas, values from 0.5 to 1.5 are small valley bottoms (on 25 m DEMs) and flatter, larger valley bottoms are represented by values from 1.

FLAG (fuzzy landscape analysis GIS; Roberts et al., 1997) combines two normalised indices calculated from elevation to give locations in the local landscape that are low and have high contributing areas. Contributing area is given by the set of points connected by a continuous, monotonic uphill path, with the underlying assumption that for saturated sub-surface flow, all points connected in this way would exert some hydraulic head on the location below. The indices calculated from a DEM are local lowness and contributing area. Local lowness (LOWNESS) is calculated by smoothing the DEM using a user specified moving window to calculate mean elevation and then subtracting this from the actual surface elevation. LOWNESS is then normalised (0-1) so that locations low in the landscape are assigned high values and locations that are at or above the local landscape are assigned zero values. The contributing area (UPNESS) for any point is given by the number of cells connected by a continuous, monotonic uphill path, normalised to 0-1. These two indices are combined (LOWUP) to give locations in the local landscape that are low and have high contributing areas, i.e. high LOWNESS and high UPNESS. LOWUP is then normalised (0-1, RLOWUP).

2. METHODS

2.1. Wetland mapping

All wetlands in the catchment were mapped. All small seepage wetlands in the catchment were mapped on the ground; they had distinct boundaries and were easy to delineate. Access to seepage wetlands in riparian areas and swamps was more difficult, and three swamps were mapped from aerial photographs and the boundaries ground truthed.

Wetlands were mapped using Trimble Pro XH and Thales Mobile Mapper GPS receivers. Wetlands were delineated using the PRIMET (Tiner, 1999) method, a quick means of assessing the presence or absence of wetlands by looking for unique wetland characteristics. Boundaries were identified by the presence of > 8 cm deep organic soil (>50 % organic matter) and if required, where more than >50% of the vegetation were obligate wetland species. The GPS data was post-processed and the horizontal positional accuracy was typically sub 30 cm. A binary wetland grid was produced with a cell size of 10 m and used for all statistical analysis (Figure 1a).

2.2. Terrain indices

A filled 10 m DEM and ArcInfo 8.1 were used for the modelling. The 10 m DEM was created by resampling a 1 m DEM (Terralink International Ltd, 2006). The 1 m DEM was not produced specifically for hydrological applications and contained triangular faces, so the DEM was resampled to create a 10 m DEM. Sinks were filled to create a continuous drainage network using the ArcInfo command FILL and the filled DEM was used for all subsequent analysis.

Evaluation of model output can be approached using qualitative or quantitative methods (e.g. Merot et al., 2003; Gunter et al., 2004). In this paper we use (1) visual comparison of patterns, (2) comparison of total predicted versus actual wetland area, and (3) cell by cell (spatial coincidence of observed and modelled).

Initial assessments were made visually to check if the patterns and total area of wetland predicted were reasonable (1 and 2). Cell by cell comparisons (3) were then made, using a range of threshold values and four quantitative measures. The indices used are continuously scaled, while the ground truth map of wetlands is binary (presence or absence of wetlands). The continuous data was converted to binary data by performing a series of threshold cuts and producing a series of binary maps. For example, a continuous map cut at 1500, means that all areas with a value of 1500 or less are combined, and all areas with an index > 1500 are combined to produce a binary map. Binary maps for each threshold cut were evaluated using a 2 x 2 contingency table (Table 1).

Table 1. Contingency table for cell by cell comparison statistics.

		Actual	
		Y	N
Predicted	Y	correct positive (a)	commission (b)
	N	omission (c)	correct negative (d)

Three cell by cell quantitative measures were used to evaluate the thresholds – efficiency, discrimination and power (Table 2).

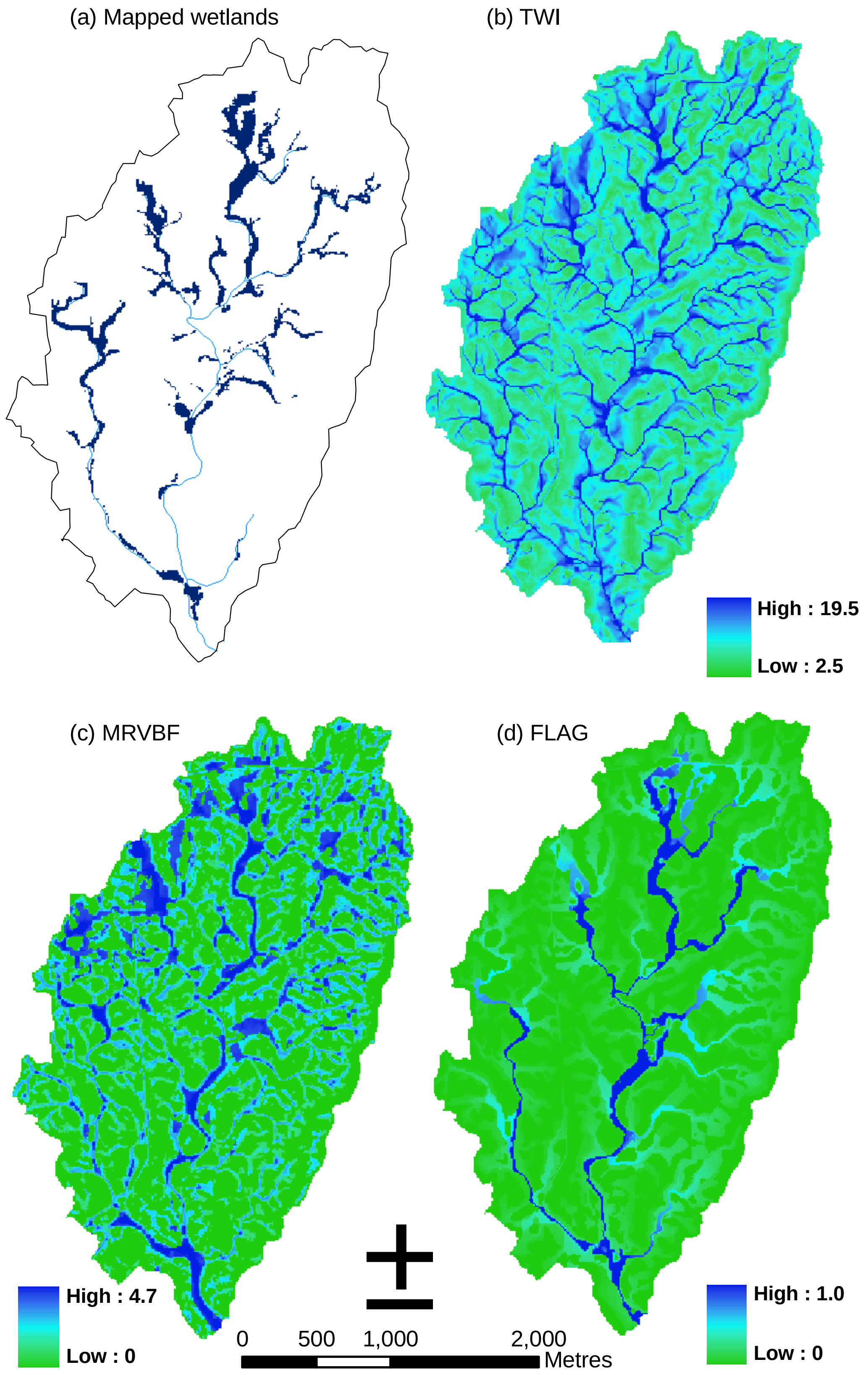

Figure 1. (a) mapped wetlands and stream network (NZMS 260), (b) TWI model, (c) MRVBF model and (d) FLAG RLOWUP model (13 cell window).

Table 2. Quantitative comparison measures (after Roberts et al., 1997).

measure	formula	comments
accuracy (overall)	$\frac{\text{predicted wetland}}{\text{actual wetland}}$	
efficiency (cell by cell)	$\frac{a}{a + c}$	$\frac{\text{correct positive}}{\text{actual wetland}}$, focuses on errors of omission
discrimination (cell by cell)	$\frac{a}{a + b}$	$\frac{\text{correct positive}}{\text{predicted wetland}}$, focuses on errors of commission
power (cell by cell)	$\left[\frac{a}{a+ b + c}\right]^{0.5}$	weights errors of commission and omission while ignoring the correct negative corrections.

3. RESULTS AND DISCUSSION

Over 5% of the farmed catchment area in the Tutaeuaua is wetland (Figure 1). There are a mix of riparian and seepage wetlands, with larger wetlands generally in the headwaters and smaller seepage wetlands in narrow steep-sided valleys and along riparian margins. Visually, the spatial pattern of potential wetlands predicted by FLAG generally agrees with the mapped wetlands as predicted wetlands are confined to valley bottoms, while MRVBF identifies additional areas distant from the stream as wetland and TWI only delineates the stream network well (Figure 1 b-d).

The topographic wetness index (TWI) identifies the stream network in some detail, but cannot predict many of the larger wetlands (Figure 1b). Threshold values in the range 7 to 12 were evaluated for a cell by cell comparison at a step of 0.5. None of the quantitative statistics identify a clear threshold value that performs well (Figure 2). The total wetland area predicted for these thresholds vary from 35 to 400 % of the mapped area, with the closest estimates occurring at thresholds of 9.5 (within 1% of mapped area) and 10 (within 20% of mapped area).

The areas with MRVBF values over 2.5 generally fall within the area identified as wetlands, although there are some areas near the northern boundary of the catchment that are incorrectly predicted as wetlands (Figure 1c). MRVBF overestimates the area of wetlands by identifying flat areas distant from the stream network, for example in the north eastern parts of the catchment (Figure 1c). While MRVBF identifies some seepage wetland cells, there are large areas of small, narrow seepage wetlands omitted from the model.

Threshold values in the range 2 to 4 were evaluated at a step of 0.02. The evaluation statistics show that between 2.6 to 2.74 the total area predicted is within 25% of the total wetland area and the power and discrimination statistics are high (Figure 2b). The total wetland area predicted for these thresholds ranges from 123 % (54.7 ha) to 72 % (26.2 ha) of the mapped wetland area (Figure 2b). Figure 3a shows that for a 2.74 threshold many of the errors of commission are located in areas distant from the stream network, while the area of wetland on the stream network is under-predicted.

With the default 13 cell window FLAG RLOWUP predicts the larger wetlands on the stream network accurately (Figure 1d), however, many of the smaller seepage wetlands are omitted. Threshold values in the range 0.01 to 1 were evaluated at a step of 0.01. The power statistic is high between 0.03 and 0.06, while discrimination is high between 0.04 and 0.1. Figure 3b shows the omitted seepage wetlands at a threshold of 0.05, for example the large ζ-shaped wetland in the centre of the catchment. At a threshold of 0.05 the total wetland area predicted is 4.67 ha (105% of mapped wetland area).

The sensitivity of the RLOWUP predictions to the LOWNESS window was assessed using windows of 5, 13, 20 and 50 cells. With a five cell window the wetlands are predicted as linear features. The 20 cell window results are similar to the default 13 cell window, although some of the larger wetlands have less detailed boundaries. For the 50 cell window the large wetlands increase in size and their outlines are less detailed (Figure 5). In this landscape, the default 13 cell window is suitable.

4. CONCLUSIONS

Small headwater wetlands are being recognised for their role in moderating stream water quantity and quality. Identifying the area and extent of headwater wetlands is important for management, and terrain indices could provide a non-controversial (Merot et al., 2006) starting point for their management.

The terrain index FLAG was able to predict the form and areal extent of wetlands, particularly swamps in the small Tutaeuaua catchment well. Neither MRVBF or FLAG was able to model small seepage wetlands well. TWI, the most frequently tested terrain index for predicting valley bottom wetlands, performed poorly.

A combination of the MRVBF and FLAG indices may have greater potential than the individual

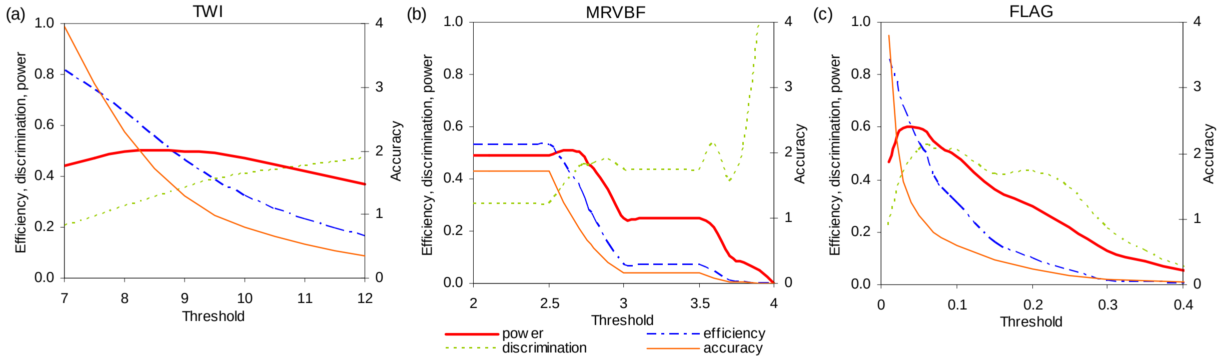

Figure 2. Quantitative overall (accuracy) and cell by cell model assessments (efficiency, discrimination, power) for (a) TWI model, (b) MRVBF model and (c) FLAG RLOWUP model (13 cell window).

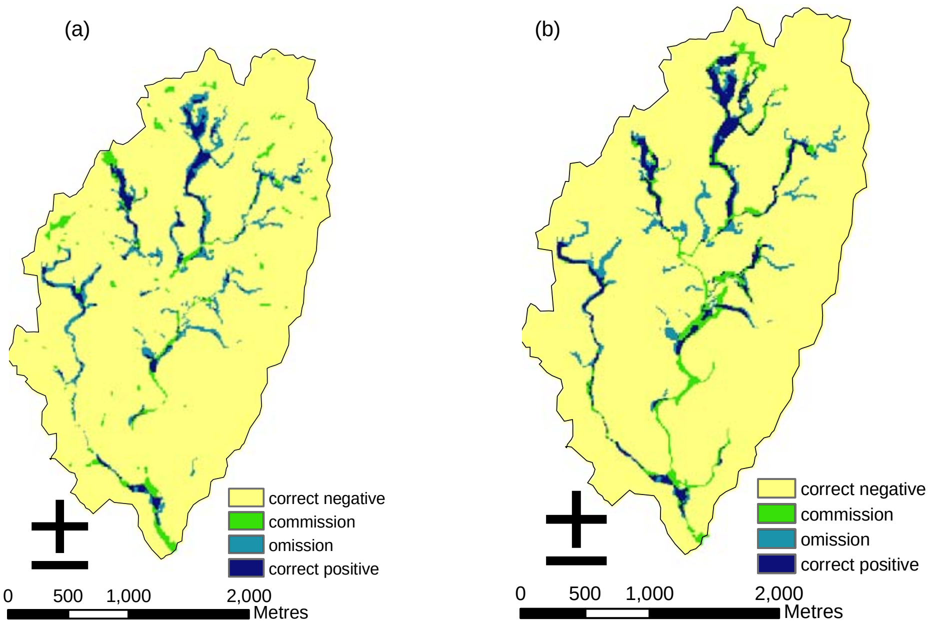

Figure 3. (a) MRVBF performance for a threshold of 2.74 (all cells with MRVBF >2.74 are wetland) and (b) FLAG RLOWUP performance for a threshold of 0.05 (all RLOWUP cells >0.05 are wetland).

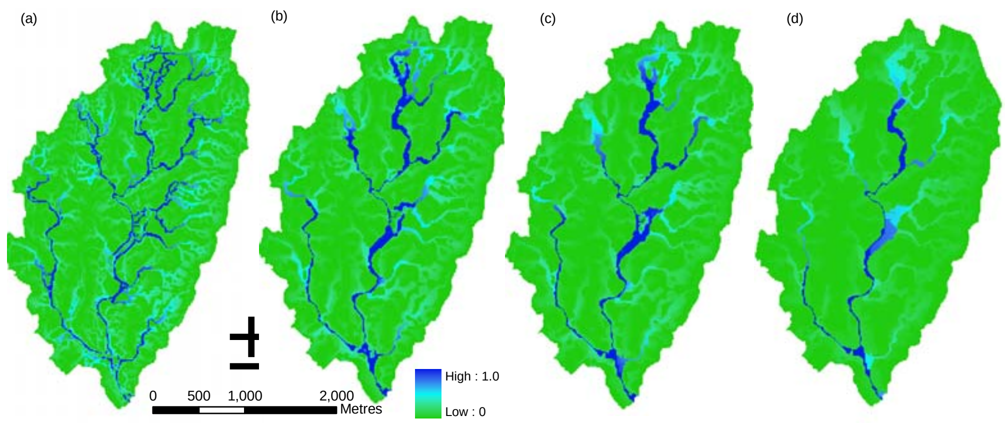

Figure 4. FLAG RLOWUP for modelled wetlands with window sizes of (a) 5 cells (b) 13 cells, (c) 20 cells (d) 50 cells.

indices. MRVBF was able to identify some hillslope seepage wetlands, while FLAG RLOWUP could be used to limit potential wetlands to the drainage network and model the extent of channel wetlands or swamps.

The terrain index FLAG presented in this study offers a useful technique for identifying the locations and areal extent of valley bottom wetlands in agricultural landscapes. The transferability of this method for predicting wetland location and extent to catchments with different physiography remains to be tested.

5. REFERENCES

Collins, R. C., 2004: Fecal contamination of pastoral wetlands. *Journal of Enviromental Quality*, 33: 1912-1918.

Dowling, T.I., Summerell, G.K. and Walker, J., (2003). Soil wetness as an indicator of stream salinity: a landscape position index approach. *Environmental Modelling & Software*, 18(6): 587-593.

Gallant, J.C. and Dowling, T.I., (2003). A multiresolution index of valley bottom flatness for mapping depositional areas. *Water Resources Research*, 39(12).

Günter, A., Seibert, J. and Uhlenbrook, S., (2004). Modelling spatial patterns of saturated areas. An evaluation of different terrain indices. *Water Resources Research*, 40: W05114.

Johnson, P. and Gerbeaux, P., (2004). Wetland types in New Zealand. Department of Conservation, Wellington.

McDonnell, J. J., 2003: Where does water go when it rains? Moving beyond the variable source area concept of rainfall-response. *Hydrological Processes*, 17:1869-1875.

McKergow, L.A., Timpany, G.C., Payne, G., (2007). Nitrogen exports from a natural wetland - baseflow, stormflow and livestock events. Proceedings of WETPOL - Second International Symposium on Wetland Pollutant Dynamics and Control. 16-20 September 2007, Tartu, Estonia.

Merot, P., Hubert-Moy, L., Gascuel-Odoux, C., Clement, B., Durand, P., Baudry, J., and Thenail, C. (2006). A method for improving the management of controversial wetland. *Environmental Management*, 37: 258-270.

Merot, P., Squividant, H., Aurousseau, P., Hefting, M. M., Burt, T.P., Maitre, V., Kruk, M. Butturini, A., Thenail, C., and Viaud, V. (2003): Testing a climato-topographic index for predicting wetlands distribution along an European climate gradient. *Ecological Modelling*, 163: 51-71.

Roberts, D.W., Dowling, T.I., Walker, J. 1997. FLAG: A fuzzy landscape analysis GIS method for landscape salinity analysis. CSIRO Land and Water Technical Report 8/97.

Rodhe, A. and Seibert, J., (1999). Wetland occurrence in relation to topography: a test for topographic indices as moisture indicators. *Agriculture and Forest Meteorology*, 98-99: 325-340.

Summerell, G.K., Dowling, T.I., Wild, J.A. and Beale, G., (2004). FLAG UPNESS and its application for mapping seasonally wet to waterlogged soils. *Australian Journal of Soil Research*, 42(2): 155-162.

Tiner, R.W. (1993). The primary indicators method - A practical approach to wetland recognition and delineation in the United States. *Wetlands*, 13(1): 50-64.

Wilson, J. P. and Gallant, J. C. , (2000). Secondary topographic attributes. In: *Terrain analysis: Principles and applications*, John Wiley & Sons, 87-132.

ACKNOWLEDGEMENTS

This research was partly funded by FRST contract C01X0304 (LAM) and CSIRO Land and Water (JCG, TID).