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Lateral flow routing into a wetland: field and model perspectives☆

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Abstract

As part of a plant succession/landscape ecology study of small, confined, emergent wetlands (boreal beaver meadows in northern Minnesota), we carried out an investigation of diffuse lateral flow of water and nutrients into the wetland from the local forested upland catchment. These local catchments may be very small (5–15 ha); flow routing is rarely considered at such a fine scale. Tape and compass surveying methods were successfully combined with GPS reference points to construct a detailed (10×10-m resolution) map of upland topography and vegetation. Analysis and modeling software were developed to trace flow from the local catchment into the meadow. Simplistic flow routing algorithms (D8) predicted uniform sheet flow with many artifacts in the predicted flow pattern, whereas a more sophisticated procedure (DEMON) suggested multiple hot spots of lateral input into the meadow along its perimeter. The flow model incorporated storage based on cover type. When considering the importance of flow from different zones in the catchment area, a simultaneous simulation of all flow to the meadow was found to be necessary to avoid serious execution order dependence. A number of edge flow collection devices were designed and installed. Collectors trapped flow across 2–3 m of meadow perimeter, and after rainfall, depending on placement, recorded flow values typically between 0 and 5–20 l/day, with peak flows in excess of 100 l/day. Concentrated points of water and nutrient input into the meadows may have a role in plant distribution and diversity.

Keywords: Runoff; Erosion; Digital terrain models; Simulation wetlands; Channel geometry

1. Introduction

As part of an ongoing investigation into small, confined, emergent wetlands (boreal beaver meadows) as landscape features in northern Minnesota (Johnston, 1994, 1995; Pastor et al., 1996), an attempt was made to measure lateral flow into a meadow. Total flow at all depths (surface, root zone, deeper clay soils, and flow at the soil/bedrock interface) was of interest. Stream flow was considered separately—well-developed methods for measuring stream flow already exist.

The study aims to quantify both water and nutrient fluxes in and out of the meadow, with the overall goal of explaining plant species distribution within the meadow. Flow across the meadow perimeter from the forested upland is believed to be a significant part of both the water and nitrogen entering the meadow.

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Direct measurement of this "lateral" flow is seldom attempted. Hydrology models generally operate at a major watershed or regional level; at that scale, these small meadows (5–15 ha) are usually represented by a small number (1–10) of GIS grid cells, and their internal flow routing is overlooked.

In this paper, we first describe instrumentation for directly recording lateral flow in the field. Then field mapping and subsequent analysis to characterize the upland catchment are outlined. Finally, models are developed with the field mapping data; and the impacts of flow routing algorithm selection, cover distribution, and simulation execution order are examined.

As an introduction to their aspect-based, stream tube flow routing model (DEMON), Costa-Cabral and Burges (1994) reviewed a range of flow routing algorithms. The D8 algorithm, which simply routes all flow from a cell to the neighboring (orthogonal or diagonal) cell with the lowest elevation, is probably the most widely used and is used by ArcInfo/ArcView. It models neither divergence nor convergence of the flow. Multiple direction methods, which assign a portion of the flow to each lower neighboring cell, model flow divergence; but Costa-Cabral and Burges found that they included cells that were not upstream of the target cell, and so "are not appropriate for contaminant [or nutrient] tracing nor can they represent distributed runoff rates."

Lateral flow routing algorithms are used not only in analyses tracing flow but in any calculation that uses the upstream contributing area, including the familiar $\ln(a/\tan\beta)$ topographic index, where a is the upstream contributing area, usually determined by flow routing, divided by the contour length, and β is the slope (e.g., Creed et al., 1996; Moore et al., 1993).

2. Study sites

"Found" meadow and "Blue Fin" meadow (Fig. 1) are on the south side of Kabetogama Peninsula in Voyageurs National Park (~ 350 m asl, 48°35′ N, 93°10′ W) in northern Minnesota. Bedrock consists of Early Precambrian granite, biotite schist, and migmatite oriented in east–west ridges (Ojakangas and Matsch, 1982). Beaver ponds and meadows occupy valley bottoms between bedrock ridges ("Blue Fin" study site: Fig. 1) and along stream corridors that traverse the ridges ("Found" study site: Fig. 1). The distance between ridge tops is typically 80–200 m, and the change in elevation from ridge top to valley floor is 3–20 m. Bedrock in the valley bottoms is overlain by up to 5 m of glaciolacustrine sediments deposited by the SE arm of Glacial Lake Agassiz (~ 11,000 years BP), and by postglacial alluvium. The E horizon of beaver meadow soils derived from glaciolacustrine sediments has a texture of silt loam to silty clay loam, and overlies a Bt horizon enriched with illuvial clays at a depth of about 0.3 m (Johnston et al., 1995). Soil texture in alluvial areas closer to

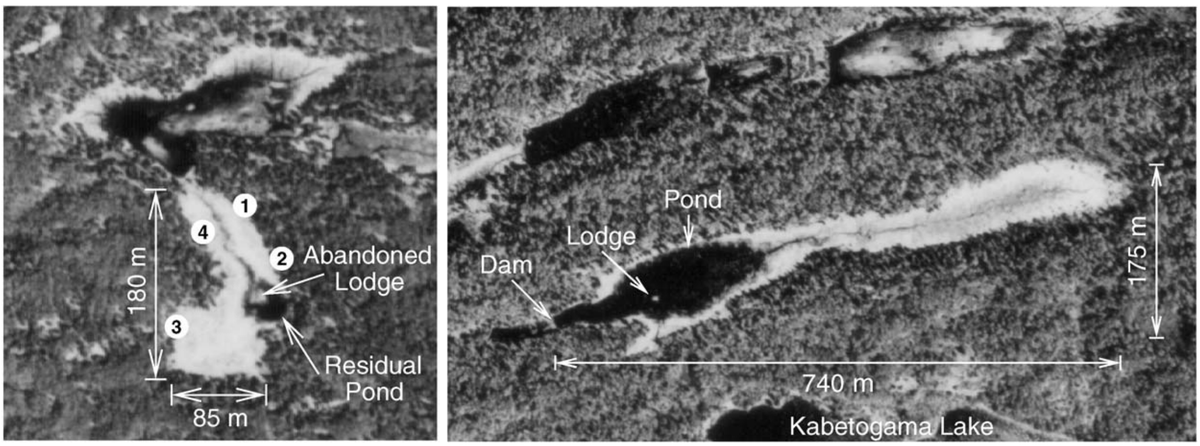

Fig. 1. "Found" (left) and "Blue Fin" study sites. Color infrared aerial photographs. Numbers indicate position of edge flow collectors in Found meadow (Table 2).

stream corridors is more variable with depth and includes sand lenses. Soils upslope of the beaver meadows are thin, with frequent bedrock outcrops, and are derived from sandy loam till deposited by the Vermillion phase of the Rainy lobe during the Wisconsin glaciation (12,000 years BP).

Both Blue Fin and Found meadows contained numerous wells, the positions of which had been precisely surveyed using differential GPS methods. These wells served as reference points for mapping of upland vegetation, and results from Blue Fin meadow are given to illustrate mapping techniques. Edge flow collectors installed in Blue Fin did not perform well; results for edge flow are reported for Found meadow only.

3. Methods

3.1. Monitoring

3.1.1. Monitoring: low slope edge flow collectors

Water volumes from the edge flow collectors (described below) were recorded twice weekly from July 1998 to November 1998 and from April 1999 to October 1999. For flow on and through gently sloping (0–10°) meadow edges, where 100–300 mm of relatively permeable soil sits over a relatively impermeable clayey layer, a buried plastic sheet was installed to collect surface and vadoze zone lateral flow (Fig. 2). A shallow triangular pit was lined with black 8 mil polyethylene sheeting on the bottom and downhill sides. The uphill side, which was perpendicular to the slope, was left open. At the downslope point of the V, a funnel spout was passed through the polyethylene, which was sealed onto the funnel body. A pipe fitted to the funnel provided drainage to a bucket. The funnel ensured the plastic sheet did not close up around the outlet pipe. A ball of plastic-coated wire mesh in the funnel mouth reduced the risk of blockage. A sunken bucket ensured sufficient head. The pit was backfilled with stones and topsoil only; no low permeability (clayey) material was returned, as this could have reduced flow from the upslope collecting face to the outlet.

3.1.2. Monitoring: high or rock slope edge flow collectors

For steep bedrock slopes with sparse soil cover, a plastic V was sealed directly to the rock (Fig. 3). Soil and moss were removed to expose the bedrock. The bedrock was carefully cleaned. Where necessary, the rock surface was dried with a propane torch to allow the polyurethane sealant (Professional Line Polyurethane TT-S-00230C, Type II Class A, ChemRex, Shakopee, MN 55379, USA) to adhere. Approximately 80 mm of the plastic was folded over on the inside (upslope side) of the V, this flap was pressed

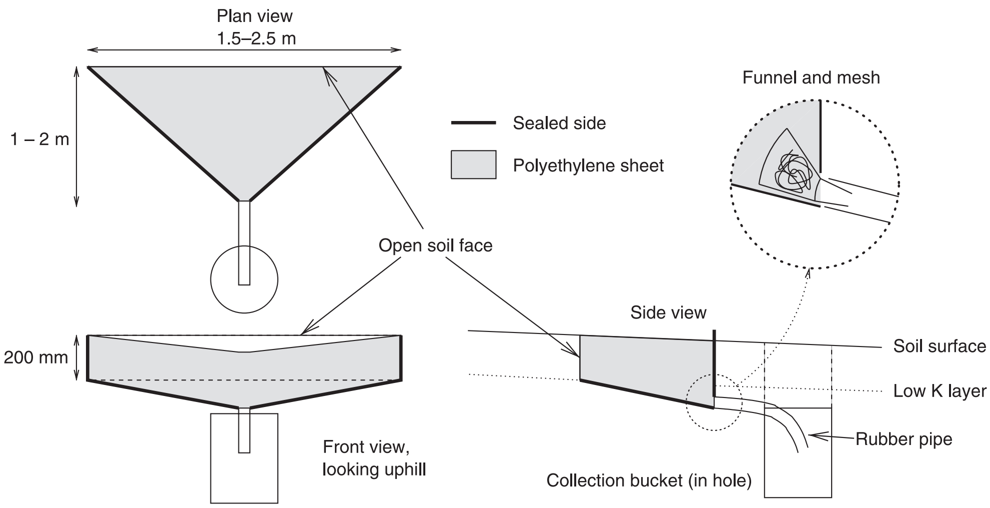

Fig. 2. Low slope soil buried edge collector.

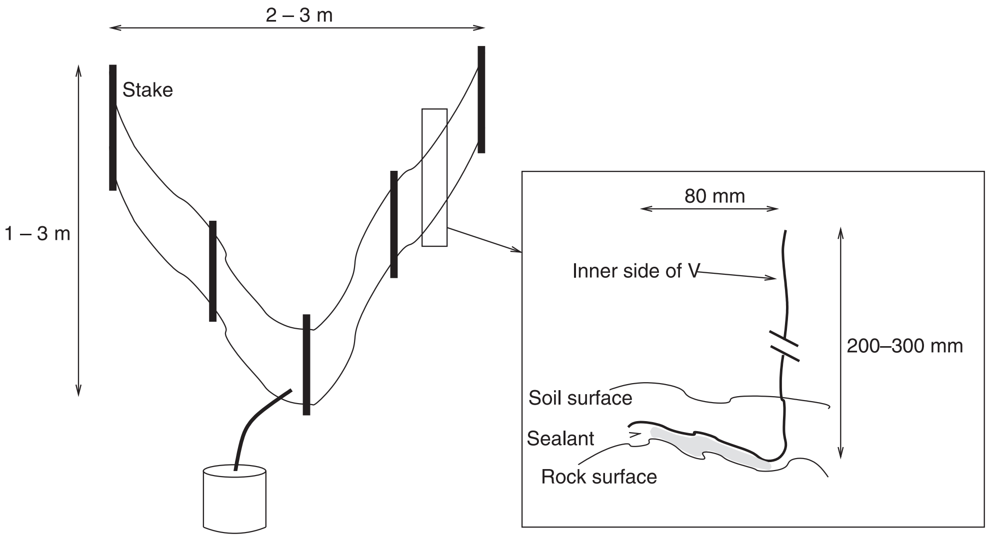

Fig. 3. Steep slope edge collector. Left view shows collector from the point of view of an observer standing down slope looking up at the collector. Closeup view on right shows a cross section of the collector wall, inner side as indicated.

into one or two beads of sealant. As with the low slope collector described above, a funnel and pipe were attached to the bottom of the V. On steep slopes, burying the bucket generally was not necessary.

3.2. Mapping

3.2.1. Mapping: field survey

A large number of transects were run from points around the edge of the meadow to the local watershed divide. The surveyed meadows contained a large number of standpipes for monitoring water table behavior. These pipes had been surveyed with ± 0.1-m accuracy using GPS equipment. The standpipes were used as starting points for each transect. A sighting compass was used to take a bearing to the closest point on the meadow perimeter, and a fiberglass tape was used to measure the distance. These offsets within the meadow were assumed to have no slope component and, in many cases, had zero length (i.e., the standpipe was on the edge of the meadow).

The rest of the transect was a series of legs where bearing, length, and slope (clinometer) were recorded by two observers. Legs were either the longest distance over which slope and cover type did not change significantly, or the longest distance over which the two observers could see each other at opposite ends—a requirement of the slope measurements. Transects were extended to the local drainage divide, i.e., the midpoint of the flat ground on the ridge. The layout of transects around part of Blue Fin meadow is shown in Fig. 4. After the three location parameters were recorded, cover type along the leg was subjectively estimated by both observers and the average recorded. The five cover types considered were bare rock, litter (including bare soil), moss, forbs (including grasses, sedges, and some small shrubs like blueberry), and trees (including larger shrubs).

3.2.2. Mapping: data analysis

Software was developed to convert the vector-based transect data into a grid-cell-based GIS cover for each grid cell in the upland. Grid cell spacing was set at 2 m. The x, y, z (easting, northing, elevation) coordinates of each node (beginning or end of leg) on the transect were calculated using the known x, y, z position of the transect reference point (stand pipe) and the lengths and angles recorded.

The contribution weighting factor W of each leg within R meters of each cell was determined from D, the shortest distance from the cell center to the transect leg (Eqs. (1) and (2)) (ERDAS, 1986). The measured slope aspect was converted into x and y components for interpolation and then back to an

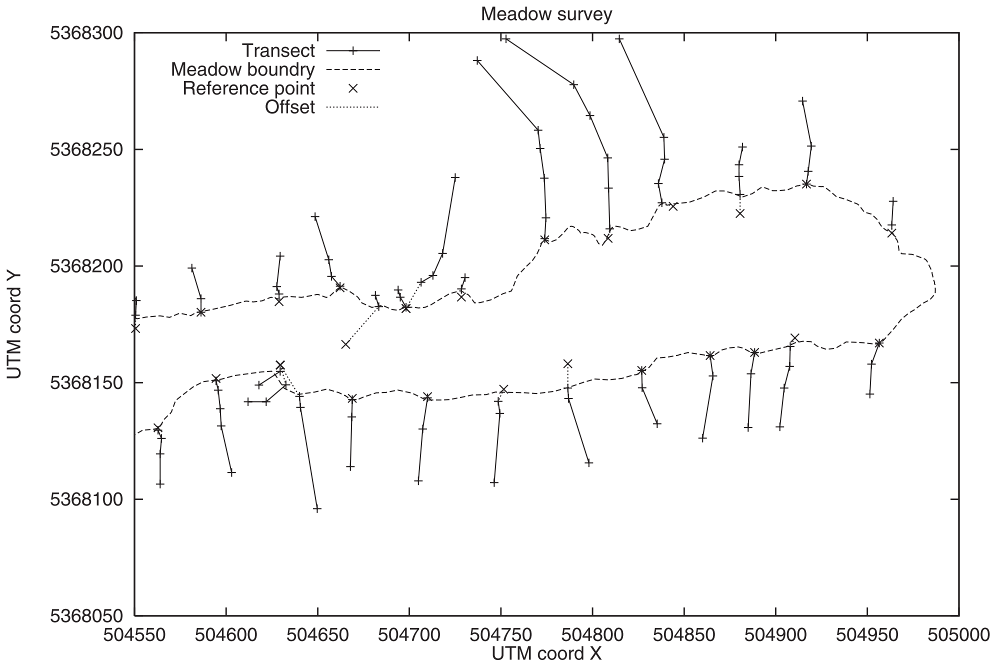

Fig. 4. Map of eastern Blue Fin meadow showing transects in the upland.

aspect so that the average of 330° and 10° is 350° rather than 175°.

$$Q = \frac{1}{\frac{R - D}{D} + 1} \quad (1)$$

$$W = e^{-0.5(5Q)^2} \quad (2)$$

3.3. Modeling

When cover type had been estimated for all grid cells, water flow was traced from each cell through other cells in the upland until it reached the meadow boundary, simulating flow resulting from rainfall over the entire area. As flow routing was the focus of this project, infiltration and storage were given a very simplistic, but consistent, treatment. The proportion p of water retained by each cell was determined as

$$p = (1 - s/90)\sum_{i=1}^{n} k_i P_i \quad (3)$$

where s is the slope in degrees, k_i (Table 1) is the proportion of available flow retained by a cell with 100% coverage of vegetation type i, and P_i is the proportion of vegetation type i in the cell. Eq. (3) gives a simple linear decrease from maximum retention with no slope to zero retention for a vertical slope. No water was retained once the cell's storage limit was reached. The storage limits (Table 1) are fairly arbitrary, as this work aims to examine the effect of the spatial distribution of substrates with different storage characteristics, and is less concerned with the storage mechanisms themselves.

Table 1
Cover type parameters used

Cover type	Capture proportion	Storage (mm)
Litter, bare ground	0.40	5
Bare rock	0.00	0
Moss	0.40	4
Trees	0.05	2
Forbs	0.30	5

Cells with tree cover type would normally also have significant litter or forb cover, hence the low value. Note that the totals are >1 due to layering of vegetation.

3.3.1. Modeling: D8 vs. DEMON

The traditional D8 (O'Callaghan and Mark, 1984) and more sophisticated DEMON (Costa-Cabral and Burges, 1994) flow routing algorithms were applied. Fig. 5 illustrates the essential differences between the two. The D8 algorithm routes all flow from a cell to the lowest neighboring cell. The DEMON algorithm uses the cell's slope aspect to split the flow between two neighboring cells, these "flow tubes" are then traced across each cell they encounter in accordance with the cell's slope aspect, splitting where their path takes them over a cell corner (Fig. 6).

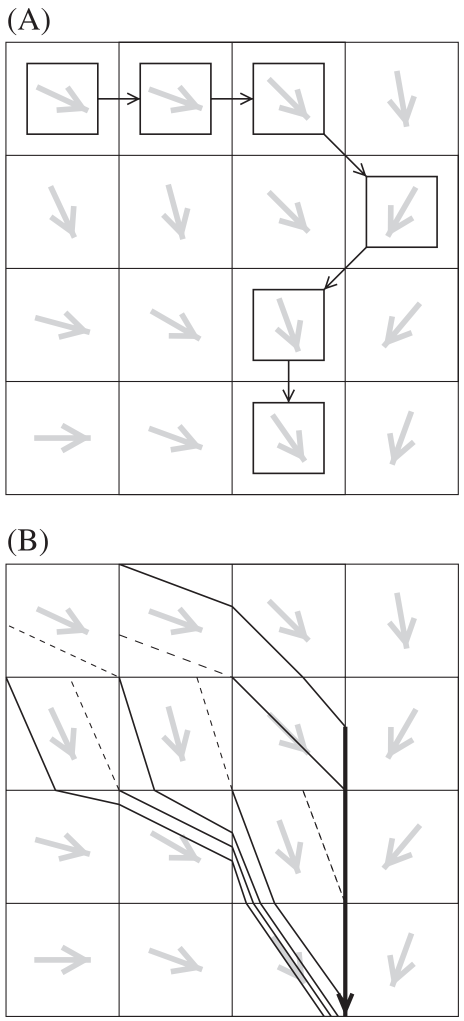

Fig. 5. Comparison of (A) D8 and (B) DEMON flow algorithms, considering only flow from the top left cell across the grid. Light arrows indicate aspect of each cell. The bold arrow in (B) indicates channel flow. DEMON "plume" spreads over more cells. Dashed lines indicate splitting of flow tubes. In (B), a drop of water placed randomly in any cell will flow across that cell in the direction dictated by the cell's aspect until it reaches the edge of the cell and enters an adjacent cell, at which point it begins to flow in the direction dictated by the new cell. Channel flow occurs when two adjacent cells both flow toward their common boundary, flow then follows that boundary. Figure after Costa-Cabral and Burges (1994).

3.3.2. Modeling: cover randomization

Upland vegetation distribution seemed likely to have some impact on lateral flow into a meadow from the upland. Consider the alternate vegetation distributions in Fig. 7. Assume each unit of vegetation type A allows 0.5 of the water flowing into it to continue downhill, and each unit of vegetation type B allows 0.9 to flow through. Then in Fig. 7A, with the simplification of a single unit of water applied at the top of the slope, $0.5^6+0.9^6=0.547066$ will flow into the meadow, whereas in Fig. 7B, $2\times0.5^3\times0.9^3=0.18225$ will flow into the meadow. In the more complex case where a unit of water is applied to each vegetation unit, the downhill sequence ABABAB gives 0.42 times as much flow into the meadow as BABABA. To investigate the effect of vegetation distribution, additional simulation runs were made with the vegetation covers randomized. Each grid cell was swapped with another cell, randomly selected.

3.3.3. Modeling: simultaneous solution

When adding storage to the model, care must be taken to avoid introducing execution order artifacts into the results. Here execution order refers to the sequence in which flow from each cell is routed by the model. Consider a slope modeled by six cells between the ridge and the meadow, as in Fig. 7. The flow originating from the top cell must be traced all the way to the meadow. As the flow moves through each cell, some of the water is retained by the cell, reducing the storage capacity of that cell. If this procedure is repeated first for the top cell, then for the cell immediately below it, and so on, by the time the flow originating from the lower cells is considered, the storage in the cells at the base of the slope may be exhausted. This will have little effect if only the total flow into the meadow is being considered, but will produce spurious results when trying to calculate the relative contributions of different parts of the upland catchment.

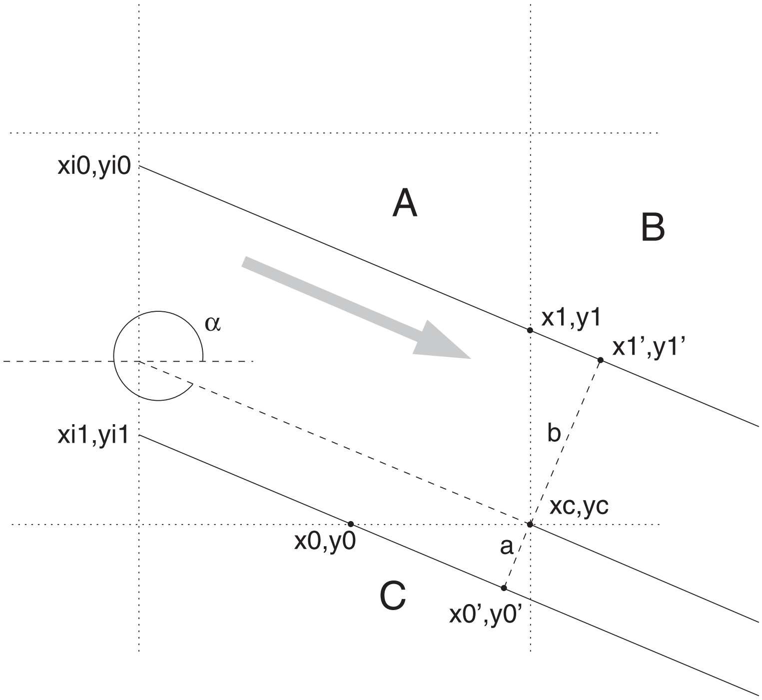

Fig. 6. DEMON algorithm flow tube splitting. A flow tube has entered cell A at points xi0,yi0 and xi1,yi1 and is flowing across cell A at the cell's slope aspect angle α. The flow is split between cells B and C according to the ratio of the lengths *a* and *b*. The proportion $a/(a+b)$ of the flow from A enters C, the remainder enters B. Initial flow from a cell is modeled by specifying a flow tube "entering" the originating cell at opposing corners, as in the top left of Fig. 5B.

The problem can be avoided, or at least reduced to the point of being inconsequential, by tracing the flow originating in each cell simultaneously. That is, the flow from every cell is advanced one step, into neighboring cells, before any flow is advanced a second step. In terms of implementation, a list of

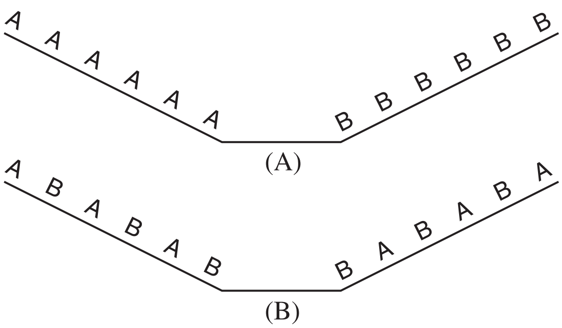

Fig. 7. Alternate distributions of vegetation on upland slopes.

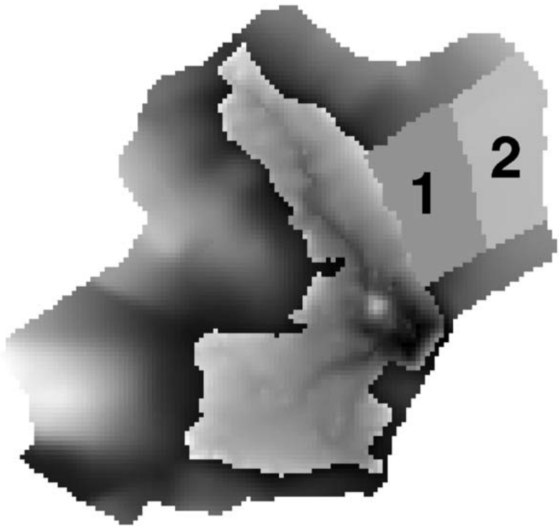

Fig. 8. Zones (1 and 2) used to compare simultaneous and nonsimultaneous solutions in the watershed of Found meadow.

flows may be used to achieve this—flows that reach the meadow are removed from the list. To test the impact of simultaneous vs. nonsimultaneous solutions, two zones (Fig. 8) of equal area, one upslope from the other, were defined. Flow from each zone was tracked with both simultaneous and nonsimultaneous solutions.

4. Results and discussion

4.1. Monitoring: edge collector readings

Fig. 9 highlights the variability in edge flow observed in Found meadow. Note the inconsistency in the relationship between sites 1 and 2 and site 3.

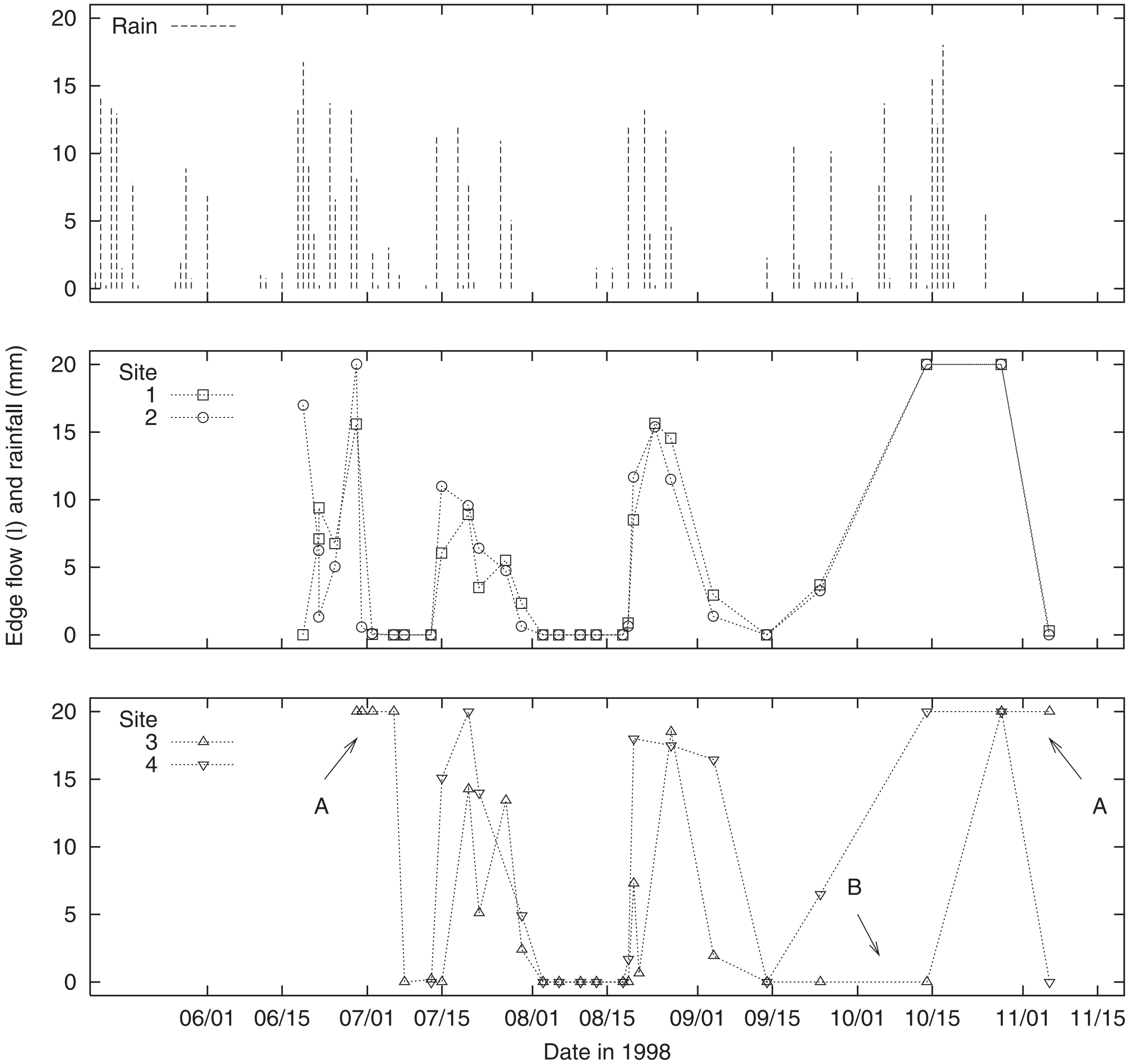

Fig. 9. Edge collector readings at four sites in "Found" meadow in 1998. Readings of 20 l indicate bucket overflow. Note A periods where output from site 3 is sustained while other sites are dry, and B period where output from site 3 is delayed.

In July, site 3 is showing major flow after 1 and 2 are dry; in October the reverse is true. Site 3 has a large, relatively flat catchment with soil depth ≥ 0.3 m, while sites 1 and 2 have smaller, steeper catchments with shallow soil and exposed bedrock. The larger catchment may have been draining in July after the prolonged wet period between June 15 and early July, while the steeper catchments of sites 1 and 2, having less storage, were more responsive to the brief rain events in September and October.

4.2. Mapping: data analysis

Meadow topography generated by the interpolation (Fig. 10) was smoother than that observed in the field, but probably represents a realistic general view. Considerable variation exists at the 1–5-m scale that cannot easily be captured by manual field survey techniques (Table 3).

In Blue Fin meadow, some banding was apparent in the interpolated results for cover type (Fig. 11). This was a consequence of the spacing and parallel nature of the transects around the meadow (Fig. 10). Table 3 summarizes the distribution of cover types for both meadows. Moss and bare rock were most likely to be completely absent in a cell, otherwise most cells had approximately the meadow-wide distribution shown in Table 3.

4.3. Modeling

4.3.1. Modeling: D8 vs. DEMON

The DEMON flow routing algorithm produced more realistic results than the D8 algorithm (Fig. 12). In Fig. 12, (A), the D8 map, is of log scale intensity, whereas (B), the DEMON map, is linear. So D8 is predicting very narrowly focused flow, whereas DEMON is predicting broader flow with a greater sheet flow component, although focused flow is still dominant. Cell-corner to cell-corner channels in the D8 map are artifacts inherent in the D8 algorithm at this scale. The light-colored horizontal stripe in the DEMON map is a real drainage divide. Its extreme linearity is due to the linear nature of the transects from which the DEM is derived.

4.3.2. Modeling: comparison with observations

The width of the edge collectors perpendicular to the direction of flow was generally about 2 m, and the model cells were 2 × 2 m. Given the overall uncertainty, comparing the flow collected by an edge collector with the flow predicted by the analysis for

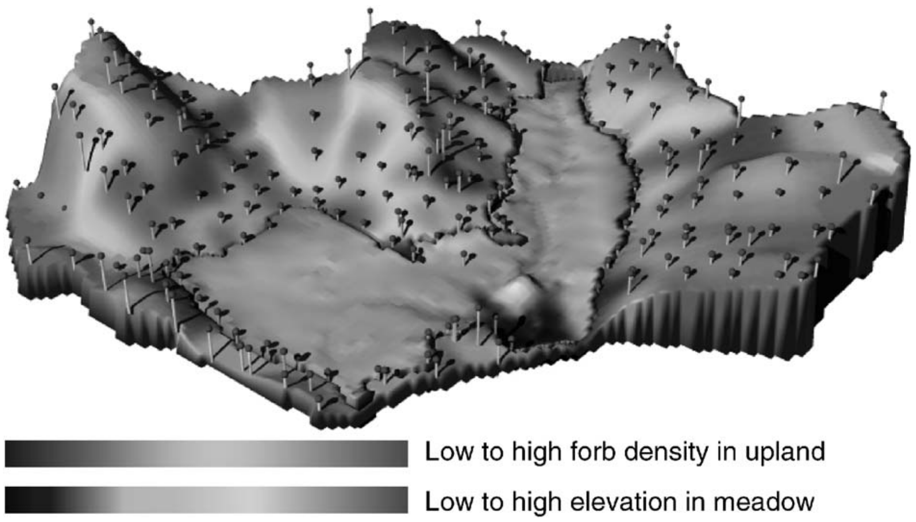

Fig. 10. Meadow topography of Found meadow and its watershed (3 × vertical exaggeration), forb distribution, and transect nodes. Map extends to local drainage divides. "Pins" indicate points on transects from upland survey.

Table 2
Characteristics of the upland draining to the four edge flow collectors

Site	Contributing area (m^2)	Aspect	Length (m)	Average slope (m/m)	Cover	Soil
1	260	226	50	0.11	Trees, forbs	1–50 cm O horizon, some mineral component at bottom of profile, rock outcrops
2	324	244	73	0.08	Trees, forbs	1–50 cm O horizon, some mineral component at bottom of profile, rock outcrops
3	260	88	81	0.15[a]	Grasses, trees	20 cm O horizon over 10–100 m Bt horizon, rock outcrops
4	232	51	53	0.11	Exposed rock, forbs, trees	Thin organic to bedrock

[a] Includes near vertical rock face of ~ 2 m, would be 0.07 without rock face.

cells in the vicinity of the edge collector seems reasonable. The mean predicted flow through all grid cells within 10 m of each edge collector was considered. Between 7 and 11 cells were within this range for the four sites in Found meadow. The means for these cells are shown in Fig. 13.

Note the change in behavior of simulated edge collector 3 at about 5 mm of rainfall, it moves from the lowest to the highest level of flow into the meadow. Edge collector 3 had a low slope catchment with ≥ 0.3 m of soil, whereas edge collectors 1, 2, and 4 had somewhat steeper catchments with less soil and more exposed bedrock. Suggesting that the change in behavior seen in Fig. 13 is similar to that observed in Fig. 9 seems reasonable. While all four simulated edge collectors show an increase in output at around 5 mm of rainfall, collector 3 jumps more dramatically and changes its relative position in the plot, moving from lowest output to highest. The model has successfully represented the change from storage-dominated flow control to catchment-topography-dominated flow control.

Fig. 11. Tree distribution in the watershed of Blue Fin meadow.

Table 3
Mean proportion (standard deviation) of each cover type in each meadow

Cover type	Found	Blue Fin
Litter/bare ground	0.15 (0.13)	0.10 (0.07)
Bare rock	0.05 (0.07)	0.07 (0.07)
Moss	0.21 (0.14)	0.08 (0.08)
Trees and shrubs	0.70 (0.16)	0.79 (0.11)
Forbs, grasses, sedges	0.58 (0.13)	0.66 (0.14)

Standard deviation is grid size-dependent, figures shown are for a 2×2-m grid.

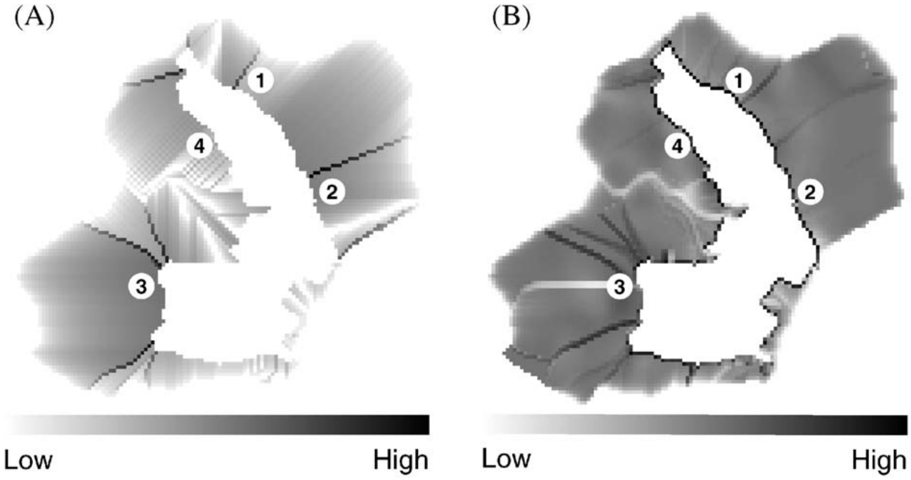

Fig. 12. (A) D8 and (B) DEMON flow algorithm results for the watershed of Found meadow. Very light areas indicate drainage divides; very dark areas, channel flow. Notice artifacts in (A). Dark cells at meadow edge in (B) indicate edge input flow, not visible in (A) because channel flow dominates; (A) is log scale intensity, whereas (B) is linear. Edge collector 3 appears to be at the bottom of a west–east drainage divide in (B)—in reality the fine-scale topography of the slope would not permit such a linear drainage divide, the interpolation of the topography data has created this effect.

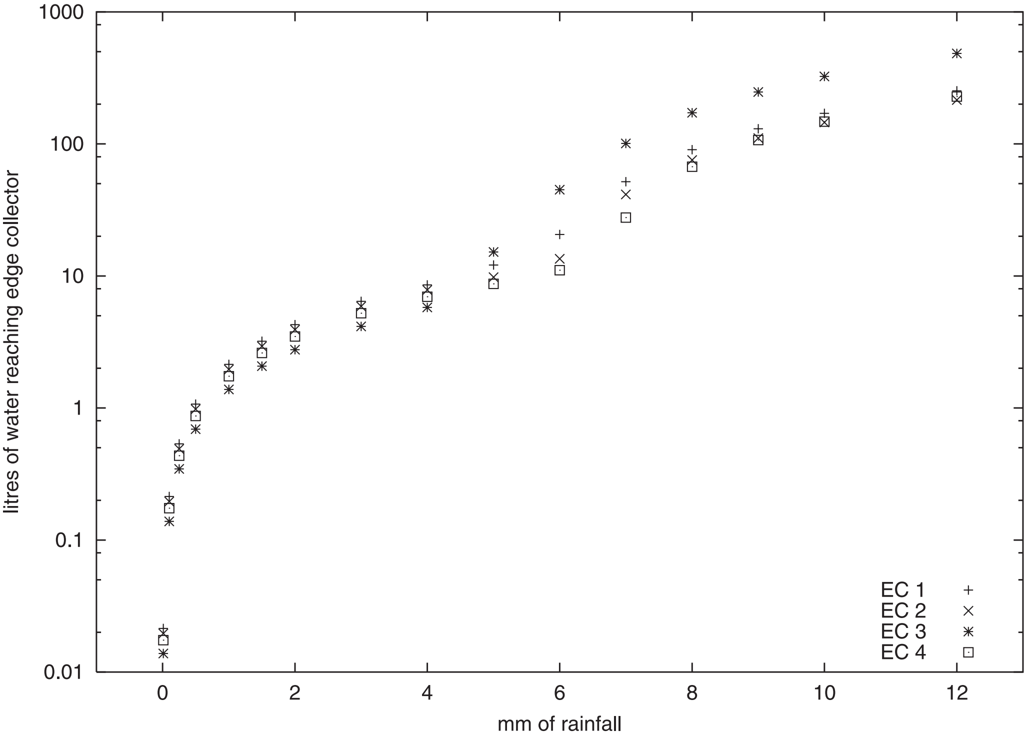

Fig. 13. Modeled upland to meadow flow at edge collector positions. Note that edge collector 3 moves from lowest to highest flow at about 5 mm of rain.

4.3.3. Modeling: cover randomization

The impact of randomly distributing plant cover in the more complex meadow system was less significant (Table 4) than in the hypothetical case in Fig. 7. The role of plants is secondary to topography, hence the greater effect of plant cover randomization when the slope effect on retention (Eq. (3)) was removed in the simulation. That the change should be negative, i.e., that randomizing the vegetation covers should reduce the amount of water flowing into the meadow, is to be expected. As in Fig. 7, mixing the vegetation types eliminates the low retention regions that contribute the most water to the meadow.

4.3.4. Modeling: simultaneous solution

As predicted, the relative contributions from zones 1 and 2 (Fig. 8) varied significantly when simultaneous and nonsimultaneous solutions were used (Table 5). Plots of simulated rainfall redistribution showed, in the nonsimultaneous case, water from zone 2 (the upslope zone) coming to rest in the storage of zone 1. In the simultaneous case, this storage was already occupied by rain falling directly on zone 1; and the water from zone 2 flowed over it, into the meadow. The column totals in Table 5 show that the impact on the total water flow into the meadow is minor. However, if the *quality* of flow from different zones is significant, as it would be if a zone contained a source of pollution or a wetland that may remove pollutants, the nonsimultaneous solution may be very misleading. This result should be considered in the context of the findings of Detenbeck et al. (1993) and Johnston et al. (1990), who demonstrated empirically a significant impact of wetland placement in a watershed.

Table 4
Flow into meadow with random versus observed vegetation distribution

Slope effect on retention (Eq. (3)) included	Randomization of vegetation	Water into meadow
Yes	Off	1855
Yes	On	1783, − 3.9%
No	Off	6886
No	On	6228, − 9.6%

Randomization effect is more noticeable with slope effect on retention removed. Units are mm per cell, 1 mm in a 2 × 2-m cell is 4 l.

Table 5
Contribution of zones (Fig. 8) influenced by execution order

Rainfall	5 mm		10 mm		15 mm	
Simultaneous	yes	no	yes	no	yes	no
Zone 1	326	326	3094	5708	7175	11,986
Zone 2	0	0	2924	89	7245	2109
Total	326	326	6018	5797	14,420	14,095

Units are mm per cell, 1 mm in a 2 × 2-m cell is 4 l.

5. Discussion

The edge collector results indicate that direct measurement of lateral flow across the upland/meadow boundary can be made. Nutrient samples can be taken in the same manner. Wilcox et al. (1997) give a more complex collector design that separates flow from individual soil horizons, whereas we were concerned primarily with the total flow and nutrient loading. Peters et al. (1995) observed that for the Canadian Shield most flow occur at the bedrock soil interface on shield slopes, so sealing the collector to bedrock where possible should reduce error. McDonnell et al. (1996) suggested that bedrock topography, rather than surface topography, is the dominant factor in determining flow patterns on slopes. In terms of the flow *pattern*, this seems reasonable. However, exposed or lichen-covered bedrock will allow more flow into the meadow than bedrock under several centimeters of organic soil with forb and tree root systems, at least until the latter is completely saturated. Distribution of flow around the perimeter was patchy both in the field and in simulation results—studies that need to assess this parameter at a within-wetland scale should be wary of assuming a uniform distribution of total runoff along the perimeter.

Given well-defined reference points (GPS-fixed standpipes in this study), simple tape and compass surveying can yield useful topographic and vegetation cover maps at the 10-m scale, even under heavy canopy. Surprisingly, the impact of vegetation distribution within a catchment has a relatively minor impact on the *total* flow from the upland into the meadow. Vegetation distribution was fairly uniform; this finding may not apply to less uniform distributions.

The traditional D8 flow routing algorithm produces unrealistic results at the small meadow scale; the DEMON algorithm appears to be a viable alternative. The impact of flow routing algorithm selection on drainage network structure may also warrant further investigation. Costa-Cabral and Burges (1994) noted some differences between networks generated by D8 and DEMON algorithms. Given the importance of network structure to runoff generation (Woods and Sivapalan, 1997), a more thorough analysis may be useful.

With the incorporation of a storage term, the model appeared to predict the observed change from storage-dominated flow to catchment-topography-dominated flow as rainfall increased. This is suggestive of the relationship between ''topographically driven runoff generation and channel network structure'' described by Woods and Sivapalan (1997), although in this case the downhill flow is merely concentrated and not developed to the stage of a channel network. Flow models that incorporate a spatially distributed storage state variable may give misleading results when the origin of the flow within the watershed is of interest, unless all flows are modeled simultaneously. This effect was not observed for very small events, which is consistent with the observation of Merz and Plate (1997). Merz and Plate also saw less impact of spatial variability with very large events, and this trend was also observable in this study. The complex, interrelated pathways involved in lateral transport (Cirmo and McDonnell, 1997) may include other mechanisms that also require simultaneous solutions for accurate results.

The complexity revealed by both our field observations and modeling results suggests more research is required to investigate the impact of focused flows at the wetland edge on wetland vegetation, both in terms of hydrology and nutrient delivery.

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