Improving forest operations planning through high-resolution flow-channel and wet-areas mapping

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ABSTRACT

This article describes a mapping process designed to provide forest management with high-resolution flow-channel and wet-area maps for forest operations planning. The process requires digital elevation models (DEMs) and hydrographic data, and also portrays the likely depth to surface water across forested terrains away from any nearest surface-water features such as streams, rivers, lakes, and wetlands. Map applications involve layout of roads and trails, automated selection of best road-stream crossings, minimizing earth-moving operations during road construction, detailing in-block plans for temporary roads and channel crossings, and delineating habitats, machine-free zones and blocks for harvesting, tree planting, site preparation, and stand thinning. Map verifications centre on visual comparisons of map features with land-surface images, and these can be coupled with GPS tracking of wetland and wet-area borders, stream channels, and road-stream crossings. Further developments involve increasing the wet-areas map resolution and accuracy with LiDAR (Light Detection and Ranging) bare-ground DEMs and other fine-gridded DEMs, and expanding the applications to mapping of soils, soil properties and tree and crop productivity, to watershed and road-network management, to off-road trafficability, and to impact evaluations dealing with hydrological sensitivities and risks.

Key words: forest operations planning, geographic information systems, digital elevation models, flow-channels, wet-areas and depth-to-water maps, hydrological risks

RÉSUMÉ

Cet article décrit un processus de cartographie conçu pour fournir dans le cas de l'aménagement forestier des cartes à haute résolution du réseau d'écoulement des eaux et des zones humides pouvant être utilisées en planification des opérations forestières. Le processus requiert des modèles altimétriques numériques (MAN) et des données hydrographiques, tout en identifiant la profondeur vraisemblable de l'eau de surface sur des terrains forestiers éloignés de tous cours d'eau de surface comme les ruisseaux, les rivières, les lacs et les marécages. L'utilisation de ces cartes couvre la mise en place des routes et des chemins forestiers, la sélection automatique des meilleures traverses de cours d'eau, la réduction au minimum des opérations de transport du sol au cours de la construction de route, le détail pour chaque bloc de coupe des chemins temporaires et des traverses de cours d'eau et l'identification des limites des habitats, des zones interdites aux engins forestiers, des blocs de coupe, des zones à reboiser, des zones prévues pour la préparation de sol et les blocs d'éclaircie du peuplement. Les vérifications des cartes se concentrent sur des comparaisons visuelles des éléments de la carte avec les images de la surface du territoire, ces dernières pouvant être accompagnées d'un repérage par GPS des marécages et des limites des zones humides, des réseaux d'écoulement des eaux et des traverses de cours d'eau. Les développements en cours portent sur l'accroissement de la résolution et de la précision des cartes des zones humides au moyen de MAN des sols nus obtenus par LiDAR (Light Detection and Ranging) et autres MAN à haute résolution, ainsi que l'expansion des applications à la cartographie des sols, des propriétés du sol et de la productivité des arbres et du peuplement, à la gestion des bassins versants et des réseaux routiers, à la capacité de portance des sols hors-route et l'évaluation des effets reliés à la sensibilité hydrologique et aux risques.

Mots clés : planification des opérations forestières, systèmes d'information géographique, modèles altimétriques numériques, réseaux d'écoulement, cartes des zones humides et de la profondeur de l'eau, risques hydrologiques

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Introduction

Knowing the location of flow channels and wet areas has become an important prerequisite for risk- and cost-reducing planning and scheduling of forest operations, and for guiding and implementing environmentally beneficial forest ecosystem management practices (Andison 2003, Pulkki 2003, RIP-NET n.d.). These practices deal with the whole spectrum of operational activities that require high-resolution delineations of flow channels and wet areas at a resolution of at least 10 m. Typical activities range from road construction to harvesting and transporting wood, to site preparations and silviculture, and to designing and scheduling activities in harvest blocks. The main components needed for mapping are a digital elevation model (DEM) of sufficient grid-point density, and a hydrographic data layer locating all previously mapped lakes, streams, shorelines, and other surface-water features such as wetlands (Murphy *et al.* 2006a). The principle of the flow-channel and wet-areas mapping process is displayed in Fig. 1, with details described elsewhere (Meng *et al.* 2006; Murphy *et al.* 2006b, 2007d). This process shares similarities with other approaches (Peucker and Douglas 1975, Hornberger and Boyer 1995, Iverson *et al.* 1997, Tarboton and Shankar 1998, Boerner *et al.* 2000, Güntner *et al.* 2004) that also use DEM data to map local flow networks by way of automatically discerning topographically defined flow directions and accumulations. The process, however, also differs from these by adding a cartographic depth-to-water layer on top of the flow-channel to allow for detailed wet-areas delineation. In general, wet areas refer to portions of landscape that are likely to be saturated at the surface for extended periods throughout each year. As such, the process can also be used to

locate and delineate wet areas associated with depressions (e.g., vernal pools), toe slopes and upland areas for stream initiation. The cartographic depth-to-water index refers to the digital elevation difference between any cell (pixel) within the landscape and any nearest surface water feature or lowest points in depressions and already mapped wetlands. Away from such locations, this depth increases either very gradually in flatter terrain, or more rapidly in steep terrain. The cartographic depth-to-water value also reflects local soil wetness and drainage, with zero-depth implying fully saturated soil conditions. This article describes the mapping process in general terms, details some of the issues arising, provides case-specific illustrations, and explores further developments relevant to forestry and other fields.

DEM Sources and Mapping Issues

Digital elevation data have become available with a wide range of grid-point spacings from very fine grid point spacings (< 1 m), generally to map small areas only, to coarse spacings (e.g., 30 to 100 m or more) to map large areas. In general, higher resolution DEMs produce better flow-channel, wet-areas and depth-to-water maps than lower resolution DEMs, but even coarse-gridded DEMs lead to useful applications as well, particularly since ordinary top-end desk-top computers are still quite limited in processing large areas with very finely-gridded DEMs. There are, however, quite a few issues that need to be resolved regardless of coarse- or fine-gridded data sources. Here are some:

- The DEM and hydrographic layers need to be positioned correctly within the geographic projection system of choice to avoid misalignments.
- Even with correct geographic positioning, there needs to be conformity between all previously mapped features (lakes, streams, rivers, shorelines, islands, roads) and the DEM grid. This conformity can be achieved by merging the two data layers into one such that open water features are digitally “burned” into the DEM layer by way of GIS processing (Olivera 1996, Saunders and Maidment 1996, Simley 2004, Murphy *et al.* 2007f).
- In this, care must be taken to ensure that the hydrographic data correspond with actual surface-water features as discernable from orthorectified air photos or satellite images of sufficient resolution.
- There is often a lack of systematic connectedness or continuity between the various stream and lake segments that are part of the hydrographic database. Lack of hydrographic connections between individual stream segments,

Fig 1. Overview of the processes used to map flow channels and wet areas using a digital elevation model (DEM) and hydrographic data. Bottom right: highlights the areas for which the cartographic depth-to-water index is $<1\text{m}$ from the soil surface.

and streams and lakes may only become apparent through close pixel-to-pixel examination of the hydrographic data, and must be corrected to ensure continuity for the DEM-based flow direction and flow accumulation calculations.

- Digital xyz elevation data may contain holes and spikes. These result in DEM interpolation and flow accumulation artefacts, such as elevation ribboning, straight-line flows along steep and flat terrain, and flow blockages.
- Not all DEMs depict actual ground elevation, but depict the elevation of vegetative surfaces, such as the surfaces of forest canopies.
- Invariably, all digital elevation data contain some level of inherent horizontal and vertical uncertainties and errors depending on the method used for DEM derivation. In addition, provincially available DEMs, usually generated from photogrammetric point sampling and topographic contour lines, tend to contain elevation information at varying spatial resolution across the landscape, and tend to lack adequate resolution for steep and flat terrains. In these cases, choices pertaining to DEM interpolation method and resolution of the interpolated raster output can strongly affect the quality of the resulting elevation surfaces.

A fairly good source for DEM data with global coverage from 60° S to 60° N is the NASA Shuttle RADAR Topographic Mission (SRTM) dataset. This dataset, generated from a NASA and USGS partnership, represents a DEM grid-point coverage at 3 arc seconds (*ca.* 90 m), and is available for downloading through the CGIAR-CSI GeoPortal (CGIAR-CSI n.d.). These data, together with the more recent ASTER DEM data, reflect surface elevations at canopy instead of ground level. In forestry, this issue needs to be addressed to allow for proper flow-channel and wet-area derivations. For a recent exposé of SRTM and ASTER DEM data, see, e.g., Nikolakopoulos and Chrysoulakis (2006).

Verification

Assessing overall map conformance to field conditions is an important map derivation component (Güntner *et al.* 2004). The following summarizes a number of verification activities that have been undertaken:

- Post-harvest orthorectified aerial photos (various bands including infra red and false colour) reveal much detail about flow channels and wet areas; overlaying these images on the wet-areas map generally shows good conformance even when the map is derived from elevation data with 30-m to 90-m grid-point spacings (Murphy *et al.* 2006a).
- Almost 90% of DEM-predicted stream-road crossings were found to fall within 40 m of their field locations, as verified using Global Positioning System (GPS) technology (Murphy *et al.* 2007f). This agreement increases with increasing slope, and with increasing DEM resolution.
- Determining tree blow-down frequencies along cutblock edges revealed increased blowdown occurrences in areas where these edges traversed wet areas, as observed and mapped (Glode 2008).
- Field mapping of stream networks, wetlands, and riparian boundaries using GPS and aerial photos generally show good conformance with the DEM-derived flowchannel and wet-areas map (Murphy *et al.* 2007c, Murphy *et al.* 2007e).

- Already mapped wetland features were consistently located within areas mapped to be wet (Murphy *et al.* 2007d). In addition, the flow-channel and wet-areas map revealed the hydrologic connections between the classified wetland features.
- The precision of the map can only be as good as the DEM and the hydrographic data used to derive it. Where the input data are in error, the resultant map will be in error as well. In Eastern Canada (NB, NS) and Maine, map conformance with ground conditions (transect traversing flow channels and wet areas) were reported by field foresters and forest operations planners to be at a level of 70% to 90%.

It should be noted that the mapped depth-to-water index is a time-integrated indicator of soil moisture or drainage conditions next to surface-water features. As such, the depth-to-water index is entirely separate from local and regional groundwater table delineations and related hydro-geological surveys. In addition, topographically derived flow channels do not capture all possible paths by which water flows into and through landscapes (Devito *et al.* 2005).

Applications

The flow channel and wet-area maps are proving useful in terms of identifying areas of hydrological risks with regard to construction and maintenance of surface structures such as roads, storage depots and housing, and placement and operation of vehicles. Areas of risk imply potential loss of investments, increased operations and maintenance costs, increased soil erosion and nutrient loss and creation of new flow channels (gullies) for pollutant transfer and flooding. This mapping process is also useful for, e.g.:

- day-to-day operations planning, reconnaissance, and communications;
- on- and off-road navigation and soil trafficability assessment;
- setting priorities for soil, stream-channel and shore-line stabilization projects in forestry and watershed management;
- locating safe areas for real estate planning and development in general.

The mapping also provides an expandable cartographic framework for incorporating other information pertaining to land-use, soil survey, ecological site classification, property, and surface images (various media). Specifically for forest operations planning and management, the maps are proving useful in the following applications:

- systematically locating previously unmapped flow channels and wet areas;
- improving road layout, design and construction;
- improving harvest block layout, to cut around wet areas, to locate access trails to and within cutblocks, and the layout of landing locations;
- ensuring plantation success through better species-site matching;
- selecting appropriate machines for scarification;
- selecting appropriate operating season to avoid soil disturbance such as rutting;
- improving the location of precommercial thinning areas to avoid water-logging;
- identifying vernal pools, riparian zones and wetlands with regard to rare plants and unique habitats;

Fig 2. Areas across Canada and the U.S. for which 10-m resolution flow-channel and wet-areas maps have already been produced (70 000 000 ha altogether).

- improving everyday field reconnaissance, to identify locations with operational risks;
- improving everyday office–field communications and navigation;
- establishing and calibrating automated and high-resolution GIS-based soil, site and productivity assessments.

Fig. 2 shows the areas across Canada where the mapping process has been completed or is currently being developed at the University of New Brunswick, in co-operation with industry, government and academic partners. To date, this approach has been applied to mapping a total of 70 million ha across Canada and in the U.S.

Further Developments

The flow-channel and wet-area mapping process can be used for high-resolution mapping of soil properties and processes, because many soil processes and the deposition of soil parent materials have been or are affected by surficial water-flow patterns, starting, e.g., from sheet and rill erosion on exposed mineral in areas subject to frequent precipitation and recur-

ring snowmelts. Currently, wet-area maps are being related to the spatial distribution of soil drainage conditions, C, N, pH, soil base saturation and base cations (Ca, Mg, K) and other physical and chemical properties in forest soils (Case *et al.* 2005, Murphy *et al.* 2007b), including the mapping of hydraulic properties of soils (Balland *et al.* 2008) and machine-specific soil trafficability (Vega-Nieva *et al.* 2008). In general, the mapping process lends itself to further addressing and exploring questions concerning the space-time continuum of soil-landscapes (Grunwald 2006). The wet-areas map is also being used to model critical soil acidification loads in reference to atmospheric S and N deposition, and to account for the spatial variability of denitrification and other soil processes (Murphy *et al.* 2007a). In conjunction with the biophysical Forest Hydrology Model (ForHyM; Balland *et al.* 2006), the flow-channel, wet-areas and depth-to-water maps are being applied to the spatial modelling of permafrost (Zhang *et al.* 2007).

The mapping process itself is subject to further refinements, particularly in view of the coarse-gridded nature of provincial DEM coverages. Light Detection and Ranging

(LiDAR)-derived DEMs show great potential to improve resolution and reliability. For the most part, conventional photogrammetric DEMs have vertical accuracies ranging from 1 m to 10 m, depending on the methods used to acquire the data (Bolstad and Stowe 1994, Hodgson *et al.* 2003). Vertical accuracies of 15 cm to 1 m are possible with LiDAR (Gomes Pereira and Wicherson 1999, Hodgson *et al.* 2003, Reutebuch *et al.* 2003). LiDAR-derived DEMs lead to a much-improved capture of topographic detail at the sub-10 m scale. This translates to an improved accuracy and resolution of flow channel and wet-area maps derived from LiDAR DEMs, as opposed to conventional photogrammetric DEMs (Murphy *et al.* 2007c, Murphy *et al.* 2007e). The cost of acquiring LiDAR data is still prohibitive for many applications but costs are decreasing and, where it is available, LiDAR offers incentives for developing new hydrologic applications (Gomes Pereira and Wicherson 1999, Wehr and Lohr 1999, MacMillan *et al.* 2003).

Concluding Remarks

High-resolution flow-channel and wet-area maps provide improved hydrographic information to help guide forest operations planning, moving towards “surprise-free” operations planning and precision forestry. Applications can result in cost savings to forestry operators and reduced environmental impact in terms of sediment and nutrient loss to streams, soil disturbance and habitat disturbance. Maps with sufficient reliability for operational purposes and resolutions of 10 m can be produced using data sets that are widely available, and for large forest management areas. Producing maps at higher resolution requires acquisition of higher-resolution DEMs, produced either through traditional photogrammetric means, using new high-resolution satellite images, or LiDAR technology. Map applications are not only confined to forestry, but extend to other areas including agriculture, urban and municipal development planning, environmental impact assessments, integrated land-management and conservation practices, landscaping and landscape architecture, to name a few. For an example of a province-wide wet-areas map, see <http://www.gov.ns.ca/natr/FORESTRY/GIS/downloads.htm>.

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