Boreal forest disturbance and streamflow response, northeastern Ontario

J.M. Buttle and R.A. Metcalfe

Abstract: The effects of forest disturbance on streamflow from small (<10 km²) basins have been well documented; however, implications of such disturbance for streamflow from relatively large rivers in the Canadian boreal forest are unclear. Landsat imagery was used to determine changes in the type, amount, and location of forest disturbance in northeastern Ontario between 1985 and 1990. These were compared with streamflow responses from medium- and large-scale basins in the region. Harvesting dominated forest disturbance, and total disturbance as of 1990 ranged from 25% of basin area in the northwest part of the region to 5% in the southeast. There was limited streamflow response to land cover changes, with no definitive changes in water year runoff or peak flow magnitude and timing. This likely reflects the ability of relatively large basins to buffer the hydrologic impacts of the small degree of recent forest disturbance, combined with the influence of climatic variability on temporal trends in streamflow. However, disturbance was associated with increases in moderate and low flows from medium and large basins, respectively, which occurred largely during summer months.


Introduction

The boreal forest is the dominant forest type in Canada, covering ~3 million km² (Zoltai et al. 1988). Frequency and intensity of disturbance of forest cover by fire are increasing in some parts of the boreal region (e.g., northwestern Ontario; Stocks and Street 1983) while decreasing elsewhere (e.g., northwestern Quebec; Dansereau and Bergeron 1993). Nevertheless, there appears to be a general increase in the rate and magnitude of disturbance by harvesting in many parts of the boreal forest (Schindler 1998). Research in the boreal forest, and to a greater extent in other forest types, has shown that forest disturbance can affect a range of aspects of basin streamflow. Total runoff (water yield) generally increases with forest disturbance (Bosch and Hewlett 1982; Sahin and Hall 1996), with reduced interception and transpiration leading to greater streamflows. Total runoff increases roughly in proportion to the fraction of basin basal area harvested (Keenan and Kimmins 1993), although the exact relationship varies between regions and forest type (Sahin and Hall 1996; Stednick 1996). The literature provides “mixed messages about peak flow responses” (Thomas and Megahan 1998, p. 3402) to forest disturbance, with reports of increases (Verry et al. 1983; Jones and Grant 1996), decreases for only small peak flows (Thomas and Megahan 1998), decreases (Harr and McCorisin 1979), and no significant changes (Thomas and Megahan 1998) following harvesting. Variations in peak flow response to disturbance likely reflect intersite differences in such factors as the dominant runoff-generating process(es), climate, geology, topography, vegetation cover, soils, and the harvesting strategy employed. There is greater consensus that summer rainfalls that do not generate a streamflow response in forested basins may produce small to moderate flows in disturbed basins (Pomeroy et al. 1997). This is due to greater soil water storage resulting from reduced evaporation (Elliot et al. 1997), combined with soil compaction and enhanced potential for soil saturation and overland flow. Disturbance may also alter...
the timing of peak flows. Snow cover in disturbed areas ablates before appreciable melt in forest stands. This produces several small peak flows, rather than a large peak flow from basin-wide snowmelt (Verry et al. 1983). The date of the annual peak flow may also be advanced (Cheng 1989). There appears to be a general increase in low flows following disturbance due to wetting-up of the basin because of reductions in rain and snow interception, sublimation, and evaporation (e.g., Hartman and Scrivener 1990; Dubé et al. 1995; Prevost et al. 1999).

Most studies of the hydrological impacts of forest disturbance have been conducted at small scales (<1 to 10 km²; Bosch and Hewlett 1982; Sachs et al. 1998), and the cumulative impacts of these local disturbances on streamflow at the medium- (100 km²) or large-basin (>1000 km²) scales are unclear (Cheng 1989; Sahin and Hall 1996). Keenan and Kimmins (1993) contended that if only a small proportion of first-order basins experience increased streamflow due to harvesting, these effects are much reduced in second- and third-order basins and are often undetectable in fourth- and fifth-order streams. Cheng (1989) found significant changes in streamflow from forested basins >10 km² in area, provided a sufficient portion of the basin was harvested. Coats and Miller (1981) noted that the cumulative effects of concentrated harvesting in large basins can lead to larger impacts on major rivers relative to those in smaller basins. The validity of predicting the cumulative impact of forest disturbance on large river systems by simply scaling up experimental results from small basins has been questioned (Cheng 1989), based on such concerns as uncertainties about flood arrival times from different tributaries and the inverse relationship between the frequency of runoff events of a given magnitude and basin size (Coats and Miller 1981).

Despite the uncertainty regarding the cumulative effects of forest disturbance on the hydrology of medium- and large-scale basins, information is needed on the streamflow response to disturbance at these spatial scales in order to address the associated implications for such issues as aquatic ecology, water supply, and generation of hydroelectricity. This paper examines (i) recent forest disturbance patterns in the boreal forest of northeastern Ontario and (ii) streamflow responses from medium- and large-scale basins in the region to this disturbance.

### Materials and methods

#### Study area

The study basins are the southwestern and southern tributaries of the Moose River basin, which drains northeastern Ontario and part of western Quebec northward to James Bay (Fig. 1; Table 1). They were selected to examine the effects of forest disturbance on streamflow at the medium- (04LK001 and 04MD004, henceforth referred to as M1 and M2) and large-basin (04LJ001, 04LF001, 04LD001, and 04LB001, henceforth referred to as L1, L2, L3, and L4) scales. The basins overlie Precambrian Shield igneous and metamorphic rocks (Superior Province) of Neo- to Meso-archean age (2.5–3.4 Ga) and have limited relief and low gradients. Lower portions of the medium basins overlie till plain, while higher elevations are on lacustrine plain. Stream headwaters in the large basins originate on Shield uplands and traverse the lacustrine plain to outlets on the till plain.

Upland portions of the basins are largely mantled by well-drained orthic humoferric podzols with a stony–rocky phase, while lower elevations are dominated by well-drained gray luvisols and poorly drained mesisols and orthic gleysols (Clayton et al. 1977a, 1977b). Forests (including treed wetlands) cover from 79 (M2) to 89% (L2) of basin area. Forests in upland areas are dominated by black and white spruce, along with balsam fir, jack pine, white birch, and trembling aspen, while forested wetlands contain tamarack and black spruce. Wetlands, cutovers, lakes, and agricultural, mining, and urban areas comprise a small proportion of each basin’s surface cover (Buttle et al. 1998).

The basins are in the Df modified Köppen climate zone: continental cool summer boreal forest climate, adequate precipitation throughout the year for vegetative growth, 4 or more months with mean temperatures >10°C, and mean temperatures in the coldest month lower than –3°C (Royal Commission on the Northern Environment 1985). There is a general increase in water year (WY: 1 October of one year to 30 September of the next) precipitation from northwest to southeast across the study area, while the fraction of WY precipitation contributed by snowfall decreases along the same gradient (Table 2). Mean WY runoff ranges from ~350 to ~450 mm, while mean WY evaporation (residual of simplified water balance) ranges from ~410 to ~453 mm. Flow from L2, L3, and L4 is regulated as a result of hydroelectric dam operation. Regulation has reduced peak runoff relative to unregulated basins, with the greatest impact on flows equalled or exceeded <5% of the time (Buttle et al. 1998).

#### Disturbance

Disturbance was assessed using two classified Landsat images
from the Ontario Ministry of Natural Resources. The first was a multispectral scanner (MSS) image based on summer scenes at 100-m resolution. Scenes were taken on various dates in 1984 and 1985 to achieve cloud-free coverage of the Moose River basin. Classification employed supervised training and a maximum likelihood classifier on four bands of MSS data (White and Ellis 1987). The second image was a thematic mapper (TM) image based on summer scenes taken at 25-m resolution in 1990 and 1991. The TM classification was resampled to match the 100-m resolution of the MSS classification. Classification employed supervised training and a maximum likelihood classifier on seven bands of TM data (Spectranalysis Inc. 1997). Disturbance was classified as “cutovers” or “burns” in the MSS image and as “recent cutovers” (<10 years old), “recent burns” (<10 years old), and “old burns and cutovers” (up to 50 years old) in the TM image (Fig. 2).

To relate forest disturbance to basin streamflow, the MSS and TM images were assumed to represent conditions as of 1985 and 1990, respectively. The 1985 classification does not indicate the age of cutovers or burns, such that their state of regeneration when the imagery was taken is unknown. Therefore, cutover and burn classes on the 1985 image represent the upper bound of disturbed area, since some areas may have been in an advanced state of regeneration and may have been similar hydrologically to mature forest stands (cf. Pomeroy et al. 1997). There were no major fires in the basins during the 1976–1996 period according to data from the Fire Science and Technology Branch, Ontario Ministry of Natural Resources, and areas classified in the 1985 image as burns and in the 1990 image as recent burns represented <0.01% of the combined basin areas. Therefore, burns and recent burns were not included in the analyses. Some 1985 cutovers were classified as recent cutovers in the 1990 image. These areas would not have been harvested between 1985 and 1990 and were subtracted from recent cutovers in the 1990 image to estimate the extent of harvesting (square kilometres) between 1985 and 1990 in an area in the west-central
Fig. 2. Disturbed areas in the study basins based on the 1985 and 1990 images. Burns (1985 image) and recent burns (1990 image) comprised a minor portion of the basin areas and were not plotted.
### Table 2. Water balance summary statistics for study basins (mean ± 1 SD) (from Buttle et al. 1998).

<table>
<thead>
<tr>
<th>Basin</th>
<th>Water Survey of Canada station name</th>
<th>Period of record</th>
<th>WY precipitation (mm)</th>
<th>WY snowfall/WY precipitation</th>
<th>WY runoff (mm)</th>
<th>R:P ratio&lt;sup&gt;a&lt;/sup&gt;</th>
<th>WY evaporation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Mattawishkwia River at Hearst</td>
<td>1986–1993</td>
<td>844±76</td>
<td>0.35±0.06</td>
<td>417±103</td>
<td>0.49±0.10</td>
<td>427±75</td>
</tr>
<tr>
<td>L1</td>
<td>Missinaibi River at Mattice</td>
<td>1920–1995</td>
<td>811±100</td>
<td>0.35±0.04</td>
<td>366±85</td>
<td>0.45±0.09</td>
<td>446±91</td>
</tr>
<tr>
<td>L2</td>
<td>Kapuskasing River at Kapuskasing</td>
<td>1920–1995</td>
<td>807±98</td>
<td>0.33±0.04</td>
<td>360±78</td>
<td>0.45±0.08</td>
<td>446±89</td>
</tr>
<tr>
<td>L3</td>
<td>Groundhog River at Fauquier</td>
<td>1920–1995</td>
<td>802±97</td>
<td>0.33±0.04</td>
<td>382±80</td>
<td>0.48±0.09</td>
<td>417±87</td>
</tr>
<tr>
<td>L4</td>
<td>Mattagami River at Smooth Rock Falls</td>
<td>1920–1995</td>
<td>813±102</td>
<td>0.33±0.04</td>
<td>351±74</td>
<td>0.43±0.09</td>
<td>462±96</td>
</tr>
<tr>
<td>M2</td>
<td>Porcupine River at Hoyle</td>
<td>1977–1993</td>
<td>895±77</td>
<td>0.31±0.04</td>
<td>442±68</td>
<td>0.49±0.06</td>
<td>453±63</td>
</tr>
</tbody>
</table>

<sup>a</sup>WY runoff ÷ WY precipitation.

### Table 3. Disturbance characteristics of the study basins.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Area (km&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>49</td>
<td>7</td>
<td>209</td>
<td>922</td>
<td>603</td>
<td>1654</td>
<td>345</td>
<td>220</td>
<td>615</td>
<td>640</td>
<td>526</td>
</tr>
<tr>
<td>% of basin</td>
<td>4.3</td>
<td>0.6</td>
<td>18.3</td>
<td>10.7</td>
<td>6.7</td>
<td>18.5</td>
<td>5.0</td>
<td>3.3</td>
<td>9.1</td>
<td>5.1</td>
<td>4.4</td>
</tr>
<tr>
<td>Largest patch index (%)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.0</td>
<td>0.3</td>
<td>4.8</td>
<td>1.0</td>
<td>6.8</td>
<td>3.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>No. of patches</td>
<td>56</td>
<td>66</td>
<td>1184</td>
<td>810</td>
<td>4203</td>
<td>10 113</td>
<td>565</td>
<td>2000</td>
<td>5368</td>
<td>1031</td>
<td>3884</td>
</tr>
<tr>
<td>Patch density (no.km&lt;sup&gt;-2&lt;/sup&gt;)</td>
<td>0.05</td>
<td>0.06</td>
<td>1.04</td>
<td>0.09</td>
<td>0.49</td>
<td>1.16</td>
<td>0.08</td>
<td>0.29</td>
<td>0.78</td>
<td>0.08</td>
<td>0.31</td>
</tr>
<tr>
<td>Mean patch size (km&lt;sup&gt;2&lt;/sup&gt;)</td>
<td>0.92</td>
<td>0.12</td>
<td>0.19</td>
<td>1.02</td>
<td>0.25</td>
<td>0.14</td>
<td>0.64</td>
<td>0.15</td>
<td>0.10</td>
<td>0.64</td>
<td>0.19</td>
</tr>
<tr>
<td>CVN</td>
<td>0.141</td>
<td>0.045</td>
<td>1.140</td>
<td>0.352</td>
<td>0.510</td>
<td>0.989</td>
<td>0.204</td>
<td>0.238</td>
<td>0.608</td>
<td>0.213</td>
<td>0.288</td>
</tr>
</tbody>
</table>

<sup>b</sup>Percentage of basin area occupied by the largest patch.

**Note:** 1, cutovers; 2, areas estimated to have been harvested between 1985 and 1990; 3, old burns and cutovers on the 1990 TM image plus cutovers on the 1985 MSS image classed as recent cutovers on the 1990 TM image.
portion of the Moose River basin (Fig. 1) with the observed extent
of harvesting between 1985 and 1990 in the same area based on
Ontario Ministry of Natural Resources data. Cells subtracted from
the 1990 recent cutovers were added to the old burns and cutovers
from the 1990 TM image, and total disturbance as of 1990 within
each basin was estimated as the sum of harvesting between 1985
and 1990 plus the augmented old burns and cutovers.

The potential effect of forest disturbance on basin hydrology de-
pends on several factors in addition to the amount of disturbance
relative to basin area. These include the nature of the surface on
which disturbance occurred, the proximity of disturbed areas to
the drainage network (Thomas and Megahan 1998), and the pattern
of disturbance within the landscape (i.e., fragmented or clumped).
Relative differences in infiltration properties between surface types
could lead to variations in runoff response to the same amount of
harvesting on each surface type. Therefore, the extent of harvesting
between 1985 and 1990 on each of the major physiographic units
in the basins (Table 1) was determined. Harvesting of wetlands
generally increases water table levels (Dubé et al. 1995), and the
consequent expansion of saturated areas may enhance streamflow
generation and increase peak flows and total runoff. However,
the extent of disturbance on wetland surfaces was not assessed, since
these localized impacts were felt to be undetectable at the scale of
basins studied here.

In order to assess disturbance patterns with respect to the drain-
age network, the Euclidean distance from each cell in a basin to
the nearest water body (major stream or lake) in the basin was cal-
culated from 1 × 250,000 digital National Topographic Series drain-
age network coverage. Cumulative total basin area and total area of
forest disturbance with increasing distance from the drainage net-
work were then determined for each basin. Using Euclidean dis-
tance instead of flow pathways will tend to underestimate the true
distance of cells to the drainage network. A better estimate would
be obtained using drainage flowpaths, the accuracy of which is a
function of the basin digital topographic model used to estimate
flowpath length. However, the size of the study area and resolution
of the available provincial digital topographic model (1 × 1 km)
made derivation of flow pathways impractical.

Disturbance patterns were analysed for the 1985 and 1990 im-
ages using indices at the patch and landscape scale. Each disturb-
bance type was analysed separately within each basin. Cells
classified as one of the disturbance types were grouped into contig-
uous patches if they contained the same attribute and touched in
any of the eight possible cardinal directions. At the landscape
scale, the contiguity of disturbed patches was assessed using the
center versus neighbors (CVN) index (Murphy 1985). CVN was
calculated for each cell by assigning a 3 × 3 kernel, and the mean
was determined for each basin. The CVN is simply the num-
ber of cells different from the center cell in the kernel. Index val-
ues range from 0 (all cells of the same class) to 8 (center cell
different from all neighbors), representing a decreasing degree of
contiguity and an increasing degree of landscape fragmentation.

**Streamflow**

The paired-basin approach (with two or more basins of similar
geology, topography, soil cover, and climate) offers the best means
of assessing streamflow response to land-use change (Bosch and
Hewlett 1982) where one basin serves as a control, while land
cover on the other basin(s) is modified. However, absence of
nearby control basins that did not experience land cover changes
between 1985 and 1990 necessitated a “quasi-paired-basin ap-
proach” (Buttle 1996), with partial control at a given scale pro-
vided by the basin with the least forest disturbance during the
period (i.e., M2 was the partial control for M1, and L4 was the par-
tial control for L1, L2, and L3).

Water Survey of Canada daily mean discharges (cubic metres
per second) for all basins for the period of record (Table 2) were
converted to daily runoff (millimetres per day) to permit compari-
sion between basins of different sizes. WY runoff was calculated
for each basin for WYs with complete records. Daily total precipi-
tation and snowfall data were obtained from all Atmospheric Envi-
rionment Service climate stations operating in and around the
basins for the period 1920–1996. WY total precipitation and total
snowfall were calculated for each station by summing October–
September monthly totals. These point data were then used to com-
pute spatially averaged annual total precipitation and snowfall val-
ues for each basin for any WYs with complete runoff records, as
described in Buttle et al. (1998). WY runoff was divided by total
precipitation to obtain the WY runoff ratio.

Double-mass curves (DMCs) of cumulative runoff from M1 ver-
sus M2 and from L1, L2, and L3 versus L4 were constructed. Lin-
ear regression equations were fit to the medium-basin DMC.
Missing streamflow data for L3 required division of the runoff re-
sion equations were fit to the large-basin DMCs for each of the
1985–1993. The latter period approximated the time interval dur-
ing which forest disturbance within the basins was assessed. DMCs
of cumulative precipitation for M1 versus M2 and for L1, L2, and
L3 versus L4 were also constructed for the same time periods used
for the runoff DMCs.

In order to assess flow regulation of L2, L3, and L4 meant that the peak and low
flow response of only the unregulated basins (M1, M2, and L1)
was examined for the period of concurrent flow record
(1986–1993). Partial duration series were constructed, consisting
of all peak flows equal to or greater than the smallest annual maxi-
mum flow for the basin for the 1986–1993 period. Each peak flow
was categorized according to the type of generating event
(snowmelt versus rainfall versus rain-on-snow) using Atmospheric
Environment Service records from the nearest station. Separation
of peak flows according to generating process has assisted inter-
pretation of peak flow generation in both southern (Irvine and Drake
1987) and northern Ontario (Woo and Waylen 1984) and examina-
tion of peak flow responses to forest cover changes in southern
Ontario (Buttle 1994). An 8-day antecedent rainfall index (ARI)
was calculated for the peak flow for each basin by summing all
rain falling on the basin on the date of the peak flow and for the
7 days preceding this date. An 8-day period was also used in Woo
and Waylen’s (1984) analysis of floods in northern Ontario to ac-
count for the significant time lag between water inputs (snowmelt
or rainfall) and flood occurrence at the Water Survey of Canada
stations resulting from the large basin size and ample wetland stor-
age. Peaks were separated according to generating event assuming
that events between Julian days 1 and 140 and with 8-day ARI <
25 mm were snowmelt events, events between Julian days 1 and
140 and with 8-day ARI > 25 mm were rain-on-snow events, and
all other events were rainfall events.

Flow duration curves (FDCs, cumulative frequency curves
showing the fraction of time that specified daily runoff were
equaled or exceeded for a period of record) were determined annu-
ally for each of the unregulated basins for 1986–1993.

**Results**

**Forest disturbance**

The 1990 TM image classified 1501 km² of the area in the
west-central portion of the Moose River basin (Fig. 1) as re-
cent cutovers. However, 559 km² of these recent cutovers
were classified as cutovers in the 1985 MSS image. Removal
of these areas from the 1990 recent cutovers gave an esti-
ated harvested area of 942 km² between 1985 and 1990.
This was within ~10% of the observed harvested area of
1047 km² during the same period. Thus, our approach ap-
echo
Fig. 3. (a) Percentage of basin area within a given distance of a major stream or lake, (b) percentage of basin area within a given distance of a major stream or lake that had been disturbed as of 1990, (c) cumulative percentage of basin area that had been harvested as of 1985 within a given distance of a major stream or lake, (d) cumulative percentage of basin area that had been harvested between 1985 and 1990 within a given distance of a major stream or lake, (e) percentage of basin area within a given distance of a major stream or lake that had been harvested as of 1985, and (f) percentage of basin area within a given distance of a major stream or lake that had been harvested between 1985 and 1990.

pears to provide reasonable estimates of forest disturbance between 1985 and 1990 in the basins. There were large differences in the amount and nature of forest disturbance between basins for a given year and between years for a given basin (Fig. 2; Table 3). Prior to 1985, L1, M2, and L4 showed the greatest degree of forest
disturbance. However, only 0.2% of M2 was harvested between 1985 and 1990, while 6.7% of L1 was harvested during the same period. Total disturbance (harvesting between 1985 and 1990 plus old burns and cutovers on the 1990 TM image plus cutovers from the 1985 MSS image classed as recent cutovers on the 1990 TM image) generally declined from west to east across the study area: M1 (18.9%), L1 (25.2%), L2 (12.4%), L3 (10.8%), L4 (8.6%), and M2 (4.9%).

Harvesting intensity on major physiographic units varied between basins. For large basins, the proportion of harvesting between 1985 and 1990 on upland areas was 20% (L1), 67% (L2), 57% (L3), and 70% (L4). Most harvesting in L1 (61%) occurred on lacustrine plain. Of the medium basins, 90% of

Fig. 4. DMCs of cumulative runoff: (a) M1 versus M2 (1986–1993) and linear best fits to the DMC for the 1 January 1986 – 1 May 1992 (thick short-dashed line, \( Y = 0.845X - 0.048, r^2 = 0.997 \)) and 1 June 1992 – 14 September 1993 (thick long-dashed line, \( Y = 1.038X - 0.385, r^2 = 0.983 \)) periods and L1 (thick long-dashed line), L2 (thick short-dashed line), and L3 (solid line) versus L4 for the (b) 1920–1966 and (c) 1970–1993 periods.
harvesting between 1985 and 1990 occurred on till plain and 10% on lacustrine plain in M1. This pattern was reversed in M2, where 98% of harvesting was on lacustrine plain and only 2% on till plain.

The proportion of basin area within 1 km of major streams or lakes was greater for large compared with medium basins (Fig. 3a), suggesting that harvesting in large basins will also tend to be relatively closer to major water bodies. This was supported by the 1985 Landsat image, where the fraction of total harvesting within 1 km of major water bodies (Fig. 3c) ranged from 0.77 to 0.85 for large basins but was only 0.7 and 0.72 in M1 and M2, respectively. The fraction of total harvesting between 1985 and 1990 within 1 km of major streams and lakes was similar to 1985 results for large basins (Fig. 3d); however, it increased to 0.84 for M1 while declining to 0.29 for M2.

Distribution of harvesting intensity within each basin was determined by dividing the amount of harvesting within a given distance interval from major water bodies by the basin area within that distance interval (Figs. 3e and 3f). In almost all cases, harvesting intensity of basin area within 100–200 m of major streams and lakes was greater than that within 0–100 m. This may reflect the presence of buffer strips, which can extend 30–90 m from streams or lakes (R. Mackereth, Centre for Northern Forest Ecosystem Research, Thunder Bay, Ont., personal communication) and in which
harvesting is generally not permitted. Some basins showed consistent patterns between the two images; for example, harvesting intensity in L1 increased with distance from water bodies up to ~2.5 km and dropped markedly beyond that distance. In other cases, the degree of harvesting intensity with distance from major water bodies changed with time. Thus, the greatest harvesting intensity in L2 as of 1985 was on areas ~500 m from streams and lakes, with disturbance decreasing with distance. The 1990 image showed the reverse pattern, with harvesting intensity increasing with distance from streams or lakes and peaking at ~2.2 km. Despite this shift, distribution of total disturbance as of 1990 (Fig. 3b) in L2 was relatively uniform with distance from major water bodies. Harvesting between 1985 and 1990 in M1 and M2 was minor (Fig. 3d). However, intensity of total disturbance was much greater in M1 (Fig. 3b), where >15% of the basin within 1 km of major water bodies was disturbed by 1990, most of this in the form of old burns and cutovers.

The nature of harvesting within basins changed with time (Table 3). Mean patch size of harvested areas decreased from 1985 to 1990 in all basins, while number of patches and patch density increased in all but M2. The latter is consistent with the decrease in harvesting in this basin during the ~5-year period. Patches comprising 1990 old burns and cutovers plus 1985 cutovers classed as 1990 recent cutovers generally showed the least patch contiguity in any given basin. The exception was M2, where the 1985 cutover patches were the least contiguous of any disturbed areas in the basin. The 1990 image indicated that patches harvested between 1985 and 1990 in L1 were the least contiguous of any of the basins, with 1985 cutover patch contiguity being greatest in M1 and M2. However, the range in CVN values for 1985–1990 harvested patches between basins was small (0.025–0.510) relative to the potential range (0–8).

**Streamflow response**

**Runoff**

There was good agreement between cumulative daily run-
off from the M1 and M2 basins from 1 January 1986 to 1 May 1992 (Fig. 4a), with cumulative runoff from M1 averaging ~85% of that from M2. This relationship changed following a large event beginning 1 May 1992 in M1 (Fig. 5), when M2 generated comparatively less runoff during this 31-day period. The slope of the DMC increased significantly following 1 June 1992, such that cumulative runoff from M1 was ~4% higher than that from M2. Conversely, the DMC of cumulative precipitation for M1 versus M2 (not shown) remained linear during the 1986–1992 period.

Shifts in DMC relationships for large basins between periods (Figs. 4b and 4c; Table 4) may have resulted from systematic temporal trends in runoff from L4 due to climatic variations and (or) land-use changes. However, time series analysis of WY runoff from L4 showed no significant temporal trend during either the 1920–1966 or 1970–1993 period, which supported use of L4 as a “quasi-control” basin. DMCs of cumulative WY precipitation (not shown) indicated that precipitation in L4 generally equaled or exceeded that in L1, L2, and L3 for both the 1920–1966 and 1970–1993 periods. Cumulative runoff from L3 exceeded that from other basins during each period. The reason for this is unknown, although it is consistent with L3’s higher mean runoff/precipitation ratio relative to the other basins (Table 2).

Slope coefficients of linear best fits to DMCs from all basins were significantly >1 for all periods, with the exception of the slope coefficient for L2 versus L4 for the 1970–1984 period. Thus runoff from L1, L2, and L3 generally exceeded that from L4. This difference was more pronounced for the 1985–1993 period, and DMC slopes ranged from 5.85 (L2) to 11.99% (L1) greater than the slope of the corresponding curve for the 1920–1966 period. The increase in WY runoff relative to that expected from the 1920–1966 period can be predicted using the 1985–1993 DMC slopes, assuming a mean WY runoff of 351 mm for L4 (Table 2). Thus, WY runoff would be 44 (L1), 21 (L2), and 45 mm (L3) greater than that estimated by the DMC slopes for the 1920–1966 period.

WY runoff ratios

There were no significant temporal trends in the ratio of WY runoff to WY precipitation for medium or large basins, either for original ratios or for differences in ratios between basins. Total precipitation, total snowfall, or the fraction of WY precipitation consisting of snowfall did not explain a significant amount of the variation in runoff ratios for each basin.

Peak flows

Annual maxima in M2 were generated by snowmelt in 1986, 1987, 1988, 1989, and 1991 and by rain-on-snow in the remaining years (Fig. 5). Annual maxima at the start of the period were similar to those at the end, with no apparent temporal trend. Rainfall generated a larger number of peak flows for M2 than for M1 and L1. Most annual maxima in M1 were generated by snowmelt. The major exception was the rainfall-generated annual maximum in 1993, while rain-on-snow peak flows occurred only in 1988. Snowmelt in 1990 and 1992 generated annual maxima approximately twice those observed at the beginning of the period; however, there was no statistically significant temporal trend in the snowmelt peak flows. L1 showed a similar pattern to that of M1. Annual maxima were generated by snowmelt in almost all years, while rain-on-snow resulted in only one annual maximum flow (1988). Snowmelt in L1 also tended to generate larger peak flows later in the period relative to those seen in 1986, 1987, and 1988; however, no statistically significant trend was observed with time.

FDCs and timing of annual minimum flows

Daily mean runoffs corresponding to various flow exceedance levels were abstracted from the annual FDCs for M1, L1, and M2 (Table 5). Runoff at a given exceedance level for a particular year was expressed relative to runoff at the same exceedance level in 1986:

\[
\text{Ratio}_{\text{year} \ t} = \frac{\text{Runoff}_{\text{year} \ t} - \text{Runoff}_{1986}}{\text{Runoff}_{1986}}
\]

Ratios were determined for the 100, 75, 50, 25, 10, 5, and 1% exceedance levels. The mean ratio for M2 for all years was not significantly different from 0 for any flow exceedance level, and there were no statistically significant temporal trends in any ratios. Temporal trends in ratios for both M1 and L1 were also statistically insignificant. Mean ratios at the largest and smallest flow exceedance levels (1, 5, 75, and 100%) in M1 were not significantly different from 0 (difference of means t test); however, mean ratios were significantly >0 at the 10, 25, and 50% levels. This indicates that there had been an increase in moderate flows in the basin during the 1986–1992 period. Mean ratios at the 1, 5, 10, and 50% exceedance levels in L1 were not significantly different from 0. However, mean ratios were significantly >0 at the 25, 75, and 100% levels, indicating an increase in moderate and low flows during the 1986–1992 period.

Annual minima between 1986 and 1993 occurred either in mid- to late summer or in late winter, immediately before the onset of spring snowmelt. There was good agreement (within 1 or 2 days) between the dates of occurrence of annual minimum flow for M1 and L1. This is not surprising given the proximity of the basins. The date of annual minimum flow for these two basins and M2 agreed to within a few days in four out of eight years. There was no systematic difference between the two western basins and M2 in the remaining years. Annual minima occurred in late winter in M1 and L1 and in mid- to late summer in M2 in some years, while the reverse occurred in other years. There was also no significant correlation between annual variations in magnitude of minimum flows from the basins between 1986 and 1993.

Discussion

Most of the recent forest disturbance in the boreal forest of northeastern Ontario has resulted from harvesting, while fire (either natural or as prescribed burns) was of minimal significance at the spatial scale examined here. Harvesting patterns have changed in recent years, with mean cutblock size decreasing from 1985 to 1990. Southeastern basins in the study area experienced either no change or a decrease in harvesting activity (as a percentage of basin area) during the 1985–1990 period. Conversely, harvesting increased in other basins during this period, particularly in the northwest part
of the study area. The small range in CVN values for 1985–1990 harvested patches between basins suggests that recent harvesting in the study area involved small but relatively contiguous cutblocks that have produced a low degree of landscape fragmentation. Sachs et al. (1998) reported a similar situation in interior British Columbia, where the landscape is in the early stages of fragmentation as a result of harvesting.

Assessment of the impacts of forest disturbance on streamflow in this region is complicated by the large basin sizes, flow-regulation and limited streamflow records for some basins, lack of proper control basins, limited extent of forest disturbance, and availability of data on forest disturbance for only two instants in time. Thus, we did not observe significant changes in such properties as runoff/precipitation ratios that have been noted for small basins elsewhere in the boreal forest (e.g., Bayley et al. 1992).

Nevertheless, recent forest disturbance appears to be associated with some aspects of streamflow from medium and large basins in the region. Increased runoff from M1 relative to M2 following 1 May 1992 reflects the greater proportion of M1 that was disturbed as of 1990 (18.9 versus 4.9%). The shift in the runoff DMC for M1 versus M2 was likely not the result of changes in relative precipitation inputs to the basins, which were fairly constant during the 1986–1992 period. However, this change cannot be attributed to forest disturbance with great confidence, due to brevity of the hydrological record and lack of data on temporal changes in forest disturbance in M1 during the 1985–1990 period.

Equivocal links between forest disturbance and runoff were also apparent for the large basins. L1, L2, and L3 all demonstrated increased runoff relative to L4, particularly during the 1985–1995 period. However, these basins did not experience increased precipitation inputs relative to those for L4. Total disturbed area as of 1990 in L4 was 8.6% of basin area. Disturbance in the other large basins in excess of this “quasi-control” value was 2.2 (L3), 3.8 (L2), and 16.6% (L1). These forest cover changes are below the 20–25% threshold that must be met or exceeded to detect a measurable response in annual runoff to forest disturbance (Bosch and Hewlett 1982; Horne et al. 1993). Nevertheless, Trimble et al. (1987) and Buttle (1994) documented significant changes in annual runoff for changes in forest cover below this threshold. The increase in DMC slope for L1 is consistent with total forest disturbance, concentration of harvesting in the basin on the lacustrine plain with its comparatively low infiltration rates, mean cutblock patch size, and recent harvesting intensity in near-stream areas in L1 relative to the other large basins. The 44-mm increase in WY runoff is also bracketed by a 23-mm increase predicted for a 10% reduction in coniferous forest cover (Sahin and Hall 1996) and by a 100-mm increase in annual runoff following clear-cutting of small (<4.5 km²) boreal forest basins in north-central Ontario (Nicolson 1995). However, the slight differences in 1985–1990 harvesting activity and total disturbance between L2, L3, and L4 appear insufficient to account for the increased cumulative runoff for L2 and L3 relative to L4 during the 1985–1993 period. Increased runoff from L2 and L3 was also unrelated to distribution of recent harvesting or total disturbance with respect to major water bodies, which was similar for L2, L3, and L4. Despite the results of time series analysis of WY runoff from L4, climate change may have influenced the runoff response of the large basins. Thus, the increased WY runoff from L1 cannot be attributed to forest disturbance in the basin. Paterson et al. (1998) suggested that hydrological changes induced by climatic variations in the boreal forest may override those due to forest disturbance such as harvesting or fire for small basins, and this should be examined in future work at larger spatial scales.

Forest disturbance did not produce significant changes in peak flows in this region, regardless of the nature of the generating event. Cheng (1989) found increases in spring runoff following clear-cutting in interior British Columbia to be related to the amount of rainfall and snowmelt during April and May (Cheng 1989). We do not have information on snowmelt rates in each basin during the 1986–1993 period, and no relationship was found between the size of snowmelt-generated peak flows and snowfall during the preceding winter. Nevertheless, the similarity in annual maxima generated by snowmelt and rain-on-snow between 1986 and 1993 for M2 suggests no significant interannual changes in the intensity of snowpack ablation during this period. It may be reasonable to assume that the meteorological conditions that drive snowmelt and that are relatively independent of forest cover conditions (i.e., incoming solar radiation, rainfall, air mass wind speed, temperature, and relative humidity) are relatively similar between the basins in a given year. Thus, there is some association between the degree of forest disturbance and increases in the size of snowmelt peak flows for some years in M1 and L1. However, the change in peak flows is not as conclusive as demonstrated elsewhere (e.g., Verry et al. 1983; Cheng 1989), which may reflect the large size of the study basins combined with the relatively small fraction of the basins that were disturbed between 1985 and 1990. Rapid snowmelt runoff from disturbed areas may simply have been subsumed by the hydrological response of the large undisturbed portion of the basins.

All three basins had multiple flood peaks during snowmelt in most years, which might reflect the disturbance that all basins had undergone prior to 1986. M2 had multiple flood peaks in all but one snowmelt period, thus providing the clearest demonstration of desynchronization of flood peaks (cf. Verry et al. 1983). In addition to disturbance by harvesting, roughly 9% of M2 was impacted by urban development, agriculture, and mining as of 1990 (Buttle et al. 1998). Snowmelt in these open areas, superimposed on the clay-rich soils that dominate the basin, appeared to produce a streamflow peak that preceded that due to melt in forested parts of M2. Despite forest disturbance in M1 and L1 between 1985 and 1990, we found no evidence for increasing desynchronization of flood peaks during snowmelt. There was also no advance in the date of the initial snowmelt peak flow from any of the basins between 1986 and 1993. As with peak flow magnitude, the basins may have been too large to detect the effect of disturbance on peak flow timing.

The FDC analyses suggest that the minor forest disturbance in M2 between 1985 and 1990 did not result in significant changes in streamflow. As with the partial duration series, the FDCs indicate that while peak flows for M1 and L1 had increased in some years during the mid- to latter part of the 1986–1993 period, there were no significant temporal
trends. Timing of low flows was also independent of the degree of basin disturbance. Nevertheless, forest disturbance in M1 and L1 was associated with increases in small and moderate flows. This is consistent with studies (e.g., Hornbeck et al. 1993; Keenan and Kimmins 1993; Hartman et al. 1996) showing clear-cutting to produce the greatest streamflow increases during low-flow periods, with smaller impacts on peak flows. The results also support the scale effect in the relationship between forest disturbance and resulting streamflow changes suggested by Coats and Miller (1981). Thus, disturbance was associated with increased moderate flows in the medium basin but mainly with low flow increases in the large basin. These increases generally occurred during the summer, and the associated changes in flow levels may have important implications for aquatic communities in these rivers. This scale dependence of the hydrological response to disturbance requires further study and should be considered when assessing the cumulative impact of forest disturbance on the hydroecology of large river systems.

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