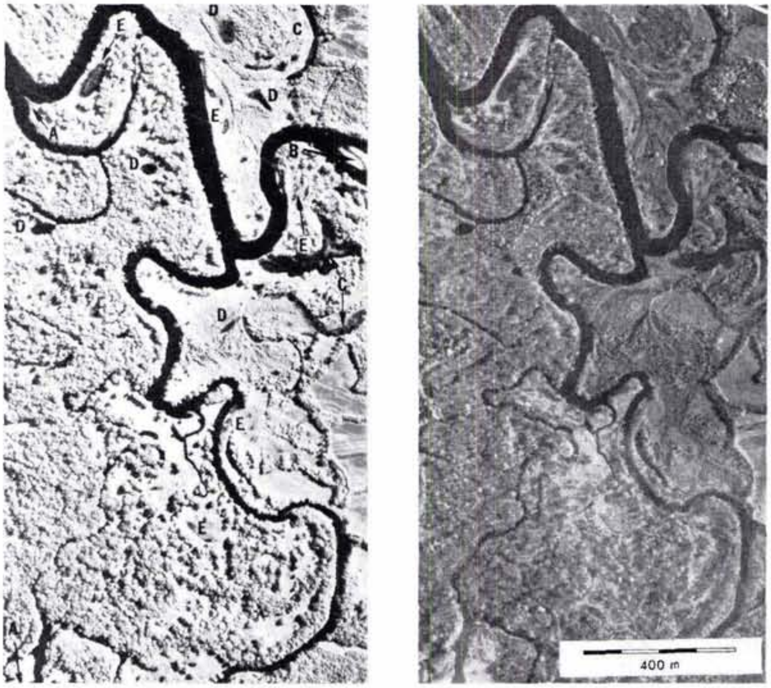

FRONTISPIECE. Panchromatic (right) and infrared air photos of part of the meander flood plain of the Oromucto River, New Brunswick. *A*, channel bar accretion—the darker toned areas represent the most recent deposits which have not yet been colonized by vegetation. *B*, minor channel through a channel bar complex. *C*, meander cut-off. *D*, back swamp. *E*, point-bar swale swamp. (Orignal scale 1:17,500)

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Infrared Photos for Drainage Analysis

Infrared aerial photographs can improve channel detection and delineation for small drainage basins of headwater type.

(*Abstract on next page*)

INTRODUCTION

REFERENCE IN THE air photo interpretation literature supports the superiority of black-and-white infrared photography over panchromatic in the detection and delineation of small water courses. As early as 1939 W. Clark[1] had commented on the low reflectance of water bodies in the actinic or near infrared wavelengths. G. C. Brock, writing in 1952,[2] noted that infrared photographs are characterised by a very dark rendering of water, and that even ditches, only a foot or so in depth, record quite black in infrared air photos. More recently, B. G. Jones[3] has commented on the value of infrared photography in mapping water levels in the inter-tidal zone, and both R. N. Colwell[4] and H. K. Meier[5] have noted that water bodies are more sharply defined against various terrain backgrounds in infrared air photos than in panchromatic. J. R. Van Lopik[6] and R. Pestrong[7] concluded that land-water contacts were more readily distinguished with infrared photography than with other types because of the greater contrast.

In addition to these specific studies, two general reviews have also dealt with the applications of infrared photography in hydrology. In 1964, C. L. Norton[8] summarized the extent to which the various United States government departments were taking advantage of the special characteristics of infrared emulsions in hydrographic investigations. More recently, the Eastman Kodak Company prepared a technical publication on applied infrared photographs,[9] including a section on the applications in hydrology. These last two references provide useful summary statements; however, apart from Pestrong's work in the rather limited environment of a tidal marsh, there is no evidence in the literature of specific studies in which the superiority of infrared emulsions for *delineating drainage systems* is actually demonstrated in a quantitative manner. Detailed comparative studies are unfortunately lacking in many aspects of air photo interpretation, and the investigation presented in the next few pages attempts to rectify this situation in a small but significant sector of the subject.

ABSTRACT: *Earth Scientists seem to have been slow in appreciating the value of special-purpose air photography. In this study, modified infrared and panchromatic air photos at medium scales were compared with regard to their effectiveness in revealing drainage networks in a forested area of New Brunswick, eastern Canada. It was found that there was more immediate recognition of water channels on the infrared photos, and considerably more network detail was detected: 73 percent compared with 39 percent for a small sample of first-order channels. For small drainage basins ranging from first- to fourth-order, the infrared photos improved channel detection by 37 percent compared with the panchromatic photos. In addition, infrared proved more effective in revealing shallow channels through bar complexes, in identifying shallow expanses of water and delimiting their margins, in differentiating between vegetated and non-vegetated point bars, in identifying aquatic vegetation and in revealing waterlogged soils.*

PURPOSE OF THE STUDY

This research was undertaken in order to obtain a specific quantitative statement of the advantages of aerial infrared photography compared with panchromatic in revealing drainage networks, and facilitating their delineation, in particular in headwater regions where individual channels are narrow and water depths are shallow.* The Gagetown area of New Brunswick was selected for the study† because of the large number of relatively short drainage networks which have developed on the irregular terrain and different rock types of the region. The average annual precipitation is 42 inches (970 mm), fairly evenly distributed through the year, and runoff accounts for the greater part of this amount, since evapotranspiration rates are low, and infiltration is restricted by the clay-rich ground moraine, which averages from three to five feet (0.9 to 1.5 m) in thickness over most of the area. The drainage network is well integrated, in part as a result of the factors mentioned above, but also because of the proximity of the area to the St. John valley and the Bay of Fundy.

Unfortunately, simultaneous multi-camera aerial photography was not available, and so the study was based on two sets of air photos obtained at different times in the summer and fall of 1962. The infrared photographs were obtained in July and August with an Aviogon lens (15-Ag-58) in a Wild RC 8 camera, focal length 152.15 mm, giving a nominal scale of 1:16,868. Exposure was made using Kodak Infrared Aerographic film type 5424 with a Wratten 12 filter, with the result that the photography is modified infrared. As indicated in Figure 1, the filter gives fairly sharp

* This study is part of a wider investigation of surface conditions and their interpretation from air photos being undertaken at McGill University. The research has been supported by the Defence Research Board of Canada, Contract GR. 7090029 Serial 2GR9–14.

† Gagetown test area-45°25′ N to 45°50′ N; 66°10′ W to 66°35′ W. Canada A.S.E. map sheet 24-x-2 (1:50,000).

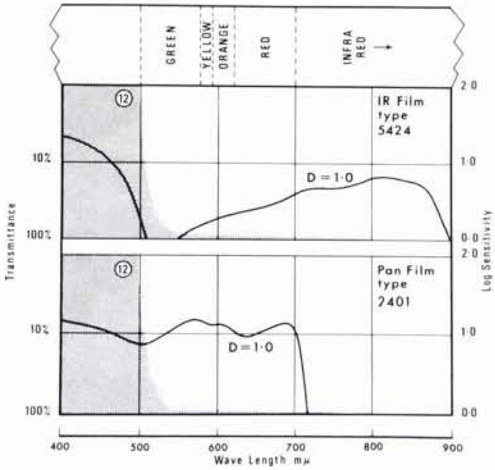

FIG. 1. Spectral sensitivity curves for Kodak film types 5424 and 2401 and Wratten No.12 filter.

cut-off at 500 mμ allowing the transmission of the longer wavelength portion of the visible energy and the actinic infrared. However, the emulsion has only limited sensitivity for wavelengths shorter than 600 mμ, and so the effective exposure is in response to reflected energy in the red and infrared portions of the spectrum between 600 and 900 mμ. The panchromatic photography was obtained in October and November 1962, with a 98094 lens in a Zeiss RMK 15/23 camera, focal length 153.04 mm, giving a nominal scale of 1:17,367. The film type was Kodak Plus X Aerographic type 2401 exposed with a Wratten 12 filter. As indicated in Figure 1, the limit of the film sensitivity is reached at approximately 720 mμ, and the filter cut-off is at 500 mμ, thus the effective exposure is in response to reflected energy in the green, yellow and red portions of the visible spectrum between 500 and 700 mμ.

The two sets of air photos are comparable in their nominal scale (infrared 1:16,868, panchromatic 1:17,367) with the infrared having a slight advantage. The resolving power of the two systems was controlled by the emulsions rather than by the lenses, and here the panchromatic photography has some slight advantage. The published Kodak data[10] give a resolving power of 40 lines/mm for Plus X Aerographic film compared with 28 lines/mm for Infrared Aerographic with a test object contrast of 1.6:1, or log luminance difference of 0.2, which corresponds to the average contrast in an air photo.

If the scale factor is considered in conjunction with the resolution factor, neither film type has any appreciable advantage as can be demonstrated by calculating the ground detection resolution for each. The ground resolution, or size of the smallest detectable ground object, is given by the empirically derived equation $D=SN/cR$ feet, where SN is the scale number, R is the limiting resolution of the photographic system, and c is 304.8, the conversion constant from the metric system. The value of D for the infrared air photos is 1.95 feet (0.53 m), compared with 1.42 feet (0.43 m) for the panchromatic, indicating that the size of the smallest detectable ground object differs by only 0.5 feet (0.10 m) from one set of air photos to the other.

The lack of synchronism between the exposure of the two films meant that the illumination angle was different for the two sets of photos and it is apparent that, in a study of this type with many sample areas, differences in the illumination angle cannot be eliminated because the solar altitude changes hour by hour. The relationship between solar altitude and the total energy return from water bodies in the photographic spectrum is far from clear; however, it is worth recording that careful experimental work by W. R. G. Atkins and H. H. Poole[11] failed to establish any progressive relationship between the extinction coefficient (or the depth at which total absorption of the transmitted illumination occurs) and the solar altitude within the range 30° to 50°. In this study the solar altitudes were between 50° and 57° for the infrared air photos, and between 35° and 40° for the panchromatic which were taken later in the season. These values are similar in range to those mentioned above, so it is reasonable to assume that no difference existed in the rendition of water channels on the two sets of air photos resulting from the effects of solar altitude on the various factors which control the total energy response, i.e., diffuse reflectance from the water surface, molecular scattering within the water, and reflectance from the channel bed. The solar altitude was sufficient to bring the solar reflection point within the format of the infrared air photos; however, areas exhibiting specular reflectance were carefully avoided in selecting the samples for study.

A more serious effect of the time lag between the exposure of the two films was the difference in ground conditions. The streams were closer to bank-full discharge in October and November than in July and August, and the vegetation cover was much reduced because the deciduous species had lost their leaves; thus the inherent visibility of the drainage networks was considerably enhanced at the time of the panchromatic photography. No way of evaluating the net advantage gained by the panchromatic film occurs as a result of these differences; nevertheless, the rendition of the drainage networks was significantly inferior on the panchromatic air photos, as will be demonstrated in the next few pages.

Field Procedures

The entire drainage network of the Gagetown area was analyzed in 1968[12], but for the purposes of this study it was impossible to consider the whole area, hence sample sections were selected at random. Many of the sample sections were visited in the field: the character of the vegetation bordering the channels was recorded, and measurements of channel characteristics, such as width and depth, were made. However, it was found that such measurements were of little value because of the variability of the channel within short distances upstream and downstream from the sample point.

Laboratory Procedure for Photo Analysis

The initial selection of sample areas was somewhat reduced by the requirement that the samples occupy positions in the center of the field of view in both a panchromatic and an infrared frame. This requirement was necessary in order to avoid the effects of radial displacement which would have introduced a bias into the measurements because a drainage channel imaged at some distance from the principal axis of a photograph is more likely to be obscured by vegetation than one imaged close to the nadir. Twenty sample areas were selected which met this requirement.

Within each selected area, a sample cell was established close to the nadir of the air photo by overlaying it with a thin cardboard mask containing a machine-cut rectangular aperture of standard size (108×56 mm) covered with Herculene polyester drafting film of 0.002 inch (0.50 mm) thickness. The masks were randomly oriented in the sample areas so that the apertures included as much of a particular drainage system as possible. The same orientation of the mask was established for each pair of air photos so as to cover an identical ground area, thus providing the sample cell. Twenty sample cells were generated in this way, giving a total of 40 overlays for the two sets of air photos.

The details of the drainage networks were traced onto the overlays by examining the respective panchromatic and infrared photos for each sample cell under a Boyer-Campbell magnifier with daylight-type fluorescent illumination. This method was preferred to stereoscopic examination because in stereo viewing there is a tendency to follow a valley or gully, even where no drainage channel is actually visible, whereas in monoscopic viewing the only reason for recording a trace is the visible presence of a channel line on the photo.*

The use of a tracing medium in the overlay reduced the visibility of the drainage networks to some extent, inasmuch as the channel segments that were marginally identifiable on the unmasked photo were not visible when the overlays were in place. However, this effect is not detrimental because the only result is to set a higher threshold of visibility, thereby narrowing the range of certainty of image identification, and eliminating the marginally identifiable situations where the subjective judgement of the interpreter becomes of critical significance. Herculene is manufactured with carefully controlled limits of thickness and density, thus the same threshold of visibility was applied in all the overlays.

The 20 overlays for the panchromatic photos were completed before the infrared photos were examined. In this way the possibility of interpretation bias resulting from the comparison, or even recollection of the detail recorded on the first overlay of a particular sample cell was eliminated.

After the completion of the tracings on all of the overlays, the total channel length recorded on each overlay was measured with a travelling micrometer. An attempt was made to enlarge the overlays in a Map-O-Graph 55; however, because of the heat generated by the illumination, it was found that the stability of the plastic was affected, thus distorting the overlay. In addition, the shadow cast by the travelling micrometer made it difficult to follow the tracing detail. The enlargement method was therefore abandoned, and the measurements were made directly on the overlays. The measured lengths were tabulated for each sample cell, and a correction

* A useful procedure for checking whether a channel is actually present is to view the photos pseudoscopically: the valley becomes a ridge and the channel, if present, stands out like a vein running across the back of one's hand.

TABLE 1. PERCENTAGE DIFFERENCE IN MEASURED CHANNEL LENGTH ON INFRARED AND PANCHROMATIC AIR PHOTOS

Sample Cell	*Total Channel Length (inches)*		*Percent Difference (D) in Total Channel Length*
	IR overlays (L_{IR})	*Pan. overlays* (L_P)	$D=\frac{L_{IR}-L_P}{L_P}\times 100$
1	11.8	11.8	0.0
2	8.0	4.6	68.9
3	21.4	16.1	32.6
4	14.5	10.6	36.7
5	3.4	2.9	17.9
6	5.1	3.3	54.8
7	12.4	11.2	10.5
8	6.4	4.8	32.3
9	4.8	1.0	366.2
10	8.9	6.2	44.1
11	9.6	5.6	72.7
12	10.2	8.7	17.9
13	5.8	4.5	28.0
14	7.6	4.7	60.5
15	6.7	4.2	58.7
16	3.4	1.0	230.2
17	9.2	7.4	24.1
18	5.6	3.5	60.0
19	6.0	4.4	35.5
20	15.1	55.5	30.9
			$\overline{D}=37.0$

factor of 1.0295 applied to the panchromatic photographs to compensate for the difference in scale. The percentage difference between the channel lengths measured on the two types of photographs was calculated for each sample cell as indicated in Table 1.

In order to discover what effect the size of the channel had on the percentage difference, a breakdown of the length measurements in each sample cell was made by stream order. The stream ordering was carried out on the air photos, and the length measurements were recorded by stream order for each sample cell. A. N. Strahler's system of stream ordering was adopted[13] since it is the most straightforward and objective. In this system (Figure 2), fingertip tributaries at the periphery of a drainage network are designated as first-order streams. The confluence of two of these first-order streams produces a second-order segment; the confluence of two second-order streams produces a third-order segment, and so on. In other words, it requires the confluence of at least two streams of any given order to form a stream segment of the next highest order. The main channel in a particular network is always the highest-order stream, and there is a progressive diminution in size down to the first-order streams. Thus, stream order is a measure of the position of a particular channel in the network hierarchy, and provides a means of ranking a channel in terms of its size where no absolute data as to width and depth are available. Such a system was suited to this study because, as mentioned previously, precise field measurements were limited.

AIR PHOTO INTERPRETATION OF DRAINAGE NETWORKS

The percentage differences between the measurements made on the panchromatic and the infrared overlays are presented in Table 1, and the superiority of the infrared photography in imaging drainage networks is apparent in 19 out of 20 sample cells. Close examination of the anomaly indicates that it results directly from the differences in ground conditions: at the time of the infrared photography the drainage network was at a lower water stage and considerably obscured by overhanging vegetation in full leaf.

Considerable variation occurs in the percentage differences in channel lengths recorded on the two film types; however, this was to be expected because the sample cells covered a variety of ground conditions and network types. The mean difference in measured channel lengths is 37 percent, which indicates that, in the Gagetown area as a whole, the information yield from the infrared photographs was more than a third greater than from the panchromatic. The comparison of the air photos and overlays from sample cell 17 (Figure 3) illustrates the greater detail

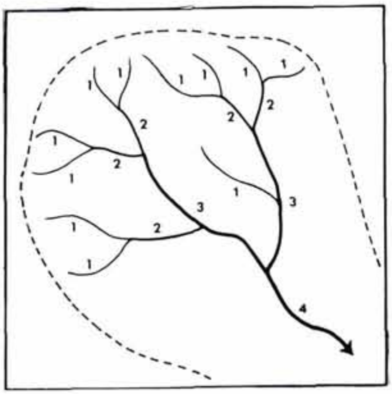

FIG. 2. System of stream ordering (adopted from A. N. Strahler). The numbers indicate the order of the respective channel segments.

recorded on the infrared photographs, and provides a general indication of the value of infrared photographs in delineating the lower-order channels in a drainage network.

This advantage is a direct result of the greater contrast range between the water bodies and the background, which consists of various types of vegetation, in the 600–900 mμ band where the infrared emulsion is most sensitive, compared with the 500–700 mμ band where the panchromatic emulsion is most responsive. These differences in the contrast range, or ratio of brightness of adjacent objects, are fundamental energy differences resulting from the extent of divergence of the reflectance spectra. The effect on the detectability of water channels can be appreciated from Figure 4 where the reflectance spectra for river water and various types of vegetation are compared. The curves are adopted from E. L. Krinov[14], and it is apparent that the contrast range between water and reed beds (*Juncaceae*), for example, is nearly eight times greater at 800 mμ where the infrared emulsion is most responsive, than at 550 mμ or 670 mμ where the panchromatic film has maximum sensitivity. The superior contrast ratio in the infrared photography, which maximizes the detectability of small water bodies and channels, can be appreciated from the Frontispiece.

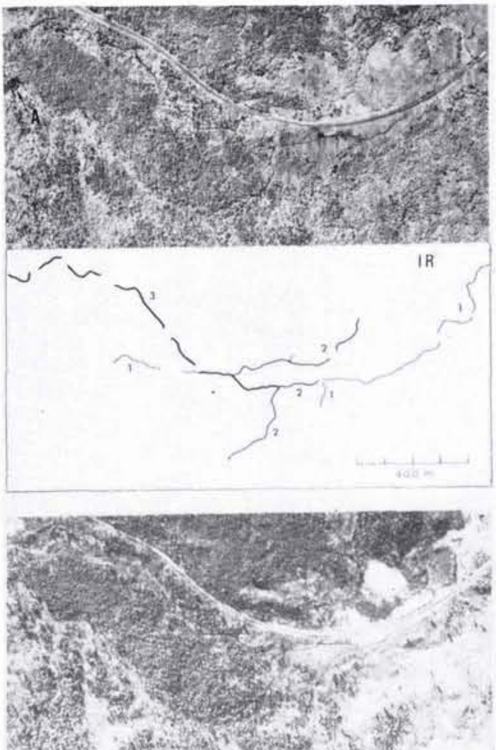

FIG. 3. Panchromatic and infrared air photos of part of a small drainage network—Gagetown, New Brunswick. A–Beaver pond.

If the measurements are considered in relation to the stream orders (Table 2) it is apparent that the maximum benefit from infrared photography is experienced for second- and third-order channels with a 43 percent advantage, respectively. The percentage difference between the measured lengths on the two film types is considerably reduced for both first- and fourth-order channels. The decrease for fourth-order streams is to be expected because with larger channels the contrast between the water and the background becomes less critical in controlling the visibility, and the advantage of the infrared emulsion is therefore reduced. The explanation for the decrease in percent difference for first-order channels is somewhat different, and probably two factors are involved. Firstly, inasmuch as first order channels are the narrowest, many of them approach the resolution limit of the film, and the presence of aquatic and phreatophytic vegetation obscures the channel shape and decreases the contrast ratio, thus the advantages of the infrared emulsion are diminished. Secondly, as first-order channels are shallower and more turbid than larger channels, the energy return will be greater as the result of scattering of the transmitted illumination by particles of suspended matter in the water and reflectance from the stream bed. The resulting increase in the total reflectance from the water decreases the contrast ratio even in the infrared wavelengths, thus the superiority of the infrared emulsion in imaging water channels is reduced.

In addition to the assessment of the relative merits of the two film types in imaging drainage networks, an attempt was made to discover what proportion of the actual channel length was recorded on each film type. As the smallest channels may be expected to yield the poorest results and so provide a minimum performance level, the analysis was

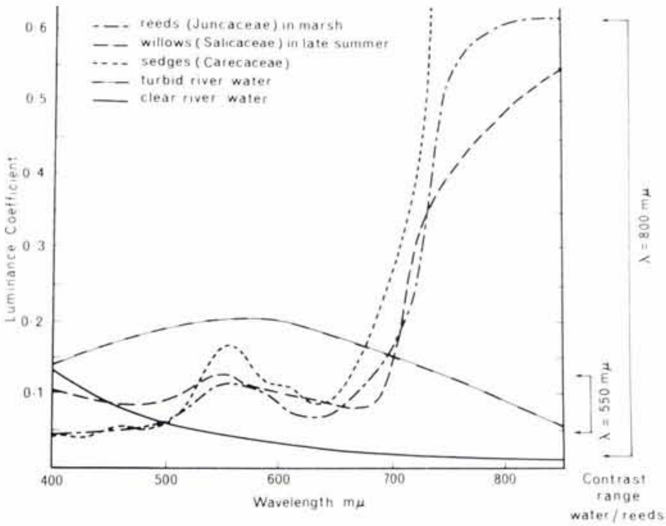

FIG. 4. Reflectance curves and contrast range for river water and various vegetation types (adapted from E. L. Krinov).

restricted to a sample of 20 first-order channels selected from within the original sample cells. The samples were all distinct channel segments originating at a seepage or gully head and terminating at the junction with another first-order channel, the ground lengths varied from 52 yards (48 m) to 1.5 miles (2400 m). The channel lengths appearing on the air photos were compared with these and it was found that the infrared emulsion had an average performance level of 73 percent compared with only 39 percent for the panchromatic. In other words, nearly a third of the actual first-order channel length was undetected on the infrared photos, whereas nearly two-thirds of the total were unrecorded on the panchromatic photos.

Several other features of interest to the geomorphologist and hydrologist were noted

TABLE 2. PERCENTAGE DIFFERENCES IN MEASURED CHANNEL LENGTH CONSIDERED BY STREAM ORDER

Stream Order	Total Channel Length (inches)		Percent Difference in Total Channel Length by Stream Order
	IR Overlays L_{IR}	Pan Overlays L_P	$D = \frac{L_{IR} - L_P}{L_P} \times 100$
1	27.8	23.3	19.3
2	48.7	33.9	43.7
3	62.9	43.8	43.6
4	15.1	11.3	33.6

in making the comparison between the two sets of sample cells. For example, the ability to differentiate between surface conditions on depositional landforms is of considerable value in the analysis of recent changes in channel characteristics, and it was found that the infrared air photos permitted immediate differentiation between bare point-bars and channel bars and those that had been colonised by grasses and small bushes (Frontispiece). This results from the greater difference in spectral reflectance between the two surface types in the infrared wavelengths compared with the panchromatic, where the contrast range is limited and the surfaces have similar tonal values. By using the infrared air photos it is possible to differentiate between the very recent depositional forms, which are not yet colonised by vegetation, and those which resulted from earlier depositional episodes and now support a cover of grasses and willow scrub (*Salicaceae*). The infrared photos were found to have an additional advantage in that shallow channels through bar complexes were clearly imaged as a result of the low energy return from the water, whereas in the panchromatic photos the channels and the bars had similar tonality due to the lower contrast range at shorter wavelengths (Frontispiece). Fording points are more apparent on infrared air photos for the same reason.

Finally, it became very apparent during the study that the infrared photos provided a much more precise indication of the presence of aquatic vegetation and of the extent of marshes and shallow inundated areas. As in the Frontispiece such conditions occur in meander flood plains due to the normal processes of fluvial erosion and deposition which give rise to backswamps, point-bar swale swamps and meander cut-offs. Shallow inundations also occur in response to biological processes such as tree fall, which may result from wind stress, stream undercutting or the activities of beaver (*Castor canadensis*). Beaver ponds can be quite large (Figure 3) and produce appreciable changes in drainage networks and their hydrological regime.

Information about shallow water bodies *per se* is of little value, but for the forester and the military tactician concerned with off-the-road mobility, or the conservationist engaged in the study of beaver and the changes in the distribution of beaver ponds from year to year, the additional information yield from infrared air photos makes the extra effort in requesting such special purpose photography well worth while.

Conclusions

This study was restricted to a few small drainage basins in a part of eastern Canada; however, it is possible to reach several conclusions which are significant at a more general level and may prove of value in hydrological research in other areas.

- The contrast ratio between water bodies and living vegetation is at a maximum in the infrared wavelengths because of the high absorption by the water and the high reflectance by the foliage, and so infrared air photos offer the best prospects within the photographic spectrum for the detection of drainage channels in forested areas.
- For small drainage basins of headwater type ranging from first- to fourth-order, modified infrared air photos, as used in this study, can improve channel detection and identification by approximately 37 percent compared with panchromatic photographs.
- The maximum benefit from infrared photography is experienced for second- and third-order channels with progressively less advantage for larger channels.
- Infrared air photos are less effective in the detection of first-order channels, particularly if they are turbid or choked with vegetation; however, they are still superior to the panchromatic. With a small sample of first-order channels it was found that 73 percent of the actual channel length was imaged on the infrared photos compared with 39 percent for the panchromatic.
- Infrared air photos have the additional advantage of revealing shallow channels through bar complexes which could be negotiated by small craft, emphasising fording points, and permitting the differentiation of fluvial depositional forms.
- Infrared air photos provide a more precise indication of the extent of shallow water inundations, such as beaver ponds, backswamps, meander cut-offs, point-bar swale swamps, and even saturated ground conditions.

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