Investigation of Land-Use Change and Groundwater–Surface Water Interaction in the Kiskatinaw River Watershed, Northeastern British Columbia (Parts of NTS 093P/01, /02, /07–/10)

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Introduction

The Kiskatinaw River watershed (KRW) comprises an environmentally critical riparian region that plays an essential role in the ecosystem of northern British Columbia. The Kiskatinaw River provides the water supply to the City of Dawson Creek, the Village of Pouce Coupe and thousands of rural residents of the Peace River Regional District. As a result, effective water-resources management within the KRW is of critical importance. However, water-resources management can be affected by a number of factors, such as the patterns of land-use change and the groundwater–surface water interaction.

On one hand, the major land-use practices in the KRW include agriculture, timber harvesting, wildlife and cattle grazing, oil-and-gas exploration, mineral-resources extraction and recreational parks (Dobson Engineering Ltd. and Urban Systems, 2003). As a world-class unconventional natural-gas reservoir, the Montney Shale gas play in the KRW is moving into the development-drilling stage. This shale-gas exploration, along with other human activities (e.g., removal of trees affected by mountain pine beetles, increasing agricultural activities) have resulted in a significant change in land-use practices. The changes of land use and land cover within the watershed may then change the hydrological patterns and pose serious challenges for the community and many other water users.

On the other hand, groundwater and surface water are closely linked components in a hydrological system, and they can be frequently exchanged. During flooding season, surface water can recharge groundwater and raise the groundwater table; however, during drought season, groundwater is an important source of water to feed the river flow. Consequently, there is a pressing need to understand the pattern of land-use change and the groundwater–surface water interaction within KRW so that informed decisions can be made for effective water-resources management.

Remote sensing is a viable means of extracting land-use and land-cover data, and hence provides effective inventory and monitoring of land-use change (Ridd and Liu, 1998; Mas, 1999). The basic principle of using remote sensing in detection of land-use change is that the change in land cover causes change in radiance value of the object (Mas, 1999), which can then be captured by the comparison of temporally varied satellite images. In remote sensing, one of the widely used approaches for assessment of land-use change is digital-image classification, where pixels in satellite images are designated with real-world land cover–type information (Matinfar et al., 2007).

The conventional per-pixel–based image classification applies supervised or unsupervised statistical techniques by taking the spectral imagery information into account but ignoring the textural and contextual imagery information (Benz et al., 2004; Matinfar et al., 2007). The supervised

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classification technique requires analyst-specified training data to classify image pixels and then group them into various land-use types, whereas the unsupervised technique is capable of classifying imagery without any prespecified training data.

In terms of groundwater–surface water interaction, different numerical methods have been applied by many researchers. For example, Hester and Doyle (2008) used several models (HEC-RAS, MODFLOW and MODPATH) to simulate coupled surface and subsurface hydraulics in a gaining stream (i.e., groundwater levels at both banks are higher than surface-water level in the stream). Hollander et al. (2009) applied a range of models (Catflow, CMF, CoupModel, Hill-Vi, HYDRUS-2D, NetThales, SUMULAT, SWAT, TOPmodel and WaSiM-ETH) to assess groundwater–surface water interactions. van Roosmalen et al. (2009) used a DK model (i.e., the National Water Resource model for Denmark), based on the MIKE-SHE code (Refsgaard and Storm, 1995), to investigate groundwater–surface water interaction under changing climatic and land-use conditions. In addition to numerical models, various hydrograph separation methods have been used to quantify groundwater–surface water interaction. For example, Eckhardt (2005) developed a low-pass filtering technique on the hydrograph in order to separate base flow. Schilling (2009) used HYSEP, an automated base-flow separation method developed by Sloto and Crouse (1996), and the PART program, a United States Geological Survey (USGS) base-flow separation method (Rutledge, 1998), to quantify groundwater recharge. Gonzales et al. (2009) used a simple graphical approach to determine the end of direct runoff contribution, where the hydrograph was plotted on a semi-logarithmic scale and the groundwater recession curve was identified as a straight line.

Since very few studies have been conducted within the KRW to investigate land-use change and groundwater–surface water interaction, the objective of this study is to fill that gap. Land-use change within the KRW from 1984 to 2010 was captured using a remote-sensing technique, and the PART program was applied to separate groundwater contribution from stream-flow records within the basin. The groundwater contribution to stream flow was quantified on a monthly time scale for a five-year period from 2007 to 2011. The gridded surface-subsurface hydrological analysis (GSSHA; Downer, 2002) was also used to determine groundwater-flow direction in the KRW.

Study Area

The Kiskatinaw River watershed (KRW) is located in northeastern BC (Figure 1). The river has its source in the foothills of the Rocky Mountains, near Tumbler Ridge, and flows approximately 200 km north before joining the Peace River at the BC-Alberta border (Forest Practices Board, 2010). The watershed is a rain-dominated hydrological system, with peak flow occurring from late June to early July. It receives an average precipitation of 499 mm during the year, comprising 320 mm of rain and 179 mm of snow. The average annual flow rate is 10 m^3/s, but it drops to 0.052 m^3/s in January (Dobson Engineering Ltd. and Urban Systems, 2003). The significant variation in river flow is a challenging issue facing water-resources management within the KRW. In fact, water demand in the City of Dawson Creek has increased at an average rate of about 3.2% per year. As shown in Figure 1, the water-intake station for the city is located in Arras, and the KRW study area was divided into five major sub-basins, including Mainstem (433 km^2), Brassey (208 km^2), Halfmoon-Oetata (194 km^2), East Kiskatinaw (996 km^2) and West Kiskatinaw (1005 km^2). The surficial geology map of the KRW (Figure 2) was digitized from Reimchen (1980). The major surficial deposits in the KRW are morainal deposits.

Methods

Detection of Land-Use Change

In this study, the advanced object-oriented classification technique was employed for capturing land-use change in the KRW, since its basic processing unit is image objects or segments containing several pixels instead of a single pixel. This technique has proven to be a better image-classifica-

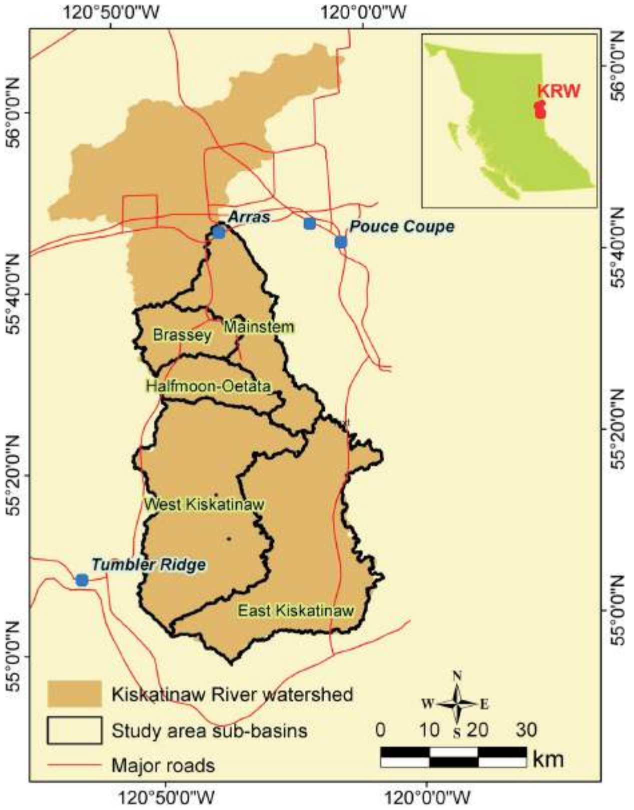

Figure 1. Major sub-basins in the Kiskatinaw River watershed study area. Communities are indicated by blue dots.

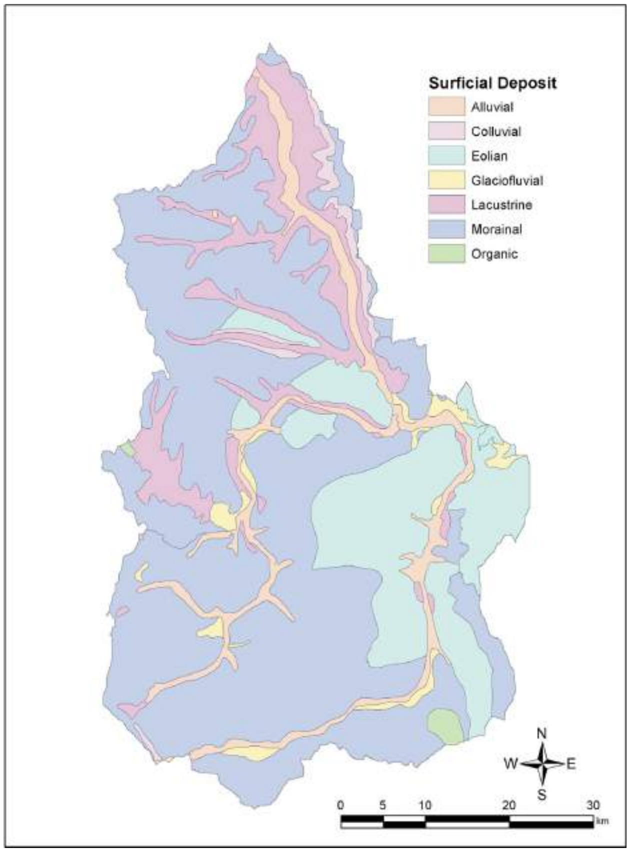

Figure 2. Surficial geology of the Kiskatinaw River watershed (after Reimchen, 1980).

tion method for detecting land-use change due to its meaningful statistics and textural calculation, and the close relation between real-world objects and image objects (Dorren et al., 2003; Matinfar et al., 2007). Landsat satellite imagery from 1984, 1999 and 2010 was used to map the land-use change. All of the imagery was downloaded from the USGS GloVis server. Table 1 lists the data description. After necessary preprocessing, including layer-stacking, georectification and mosaicing subsetting, the images were independently classified using an object-oriented algorithm to extract land-use feature classes. The IDRISI-selva software was used for the object-oriented classification, and PCI Geomatica, ArcGIS and Quantum GIS were used in different phases of the analysis.

The detailed procedure of image analysis can be summarized as follows:

1) **Step 1:** After downloading the appropriate satellite imagery, a single imagery file containing all the bands for each Landsat scene was prepared using the ‘transfer’ and ‘translate’ tools of PCI Geomatica. The two images were then mosaiced and the mosaiced image was cropped to the boundary of the KRW study area with the subsetting tool in PCI.
2) **Step 2:** Digital classification was carried out using the IDRISI-selva tools. The first task was to generate the training class, using ground-truth field data, previous maps, higher resolution satellite imagery and airphotos, to enable the segment classifier to process the imagery. The next task was image segmentation followed by digital classification of the segments using the maximum likelihood algorithm to produce the object-oriented image classification.
3) **Step 3:** An accuracy assessment of the segment classification output was carried out using the ‘accuracy assessment’ module in the IDRISI-selva software, which required a new set of ground-truth field data. Some tiny features consisting of only one or two pixels can be easily confused with other feature types in digital-image classification. The classified imagery was therefore manually edited using various GIS tools to ensure that such features were properly classified. The result was a complete land-use map of the study area for each of the three years.
4) **Step 4:** Comparative analysis of the land-use maps for 1984, 1999 and 2010 generated statistics on land-use change and enabled prediction of future land-use change scenarios based on the present trend of change.

Investigation of Groundwater–Surface Water Interaction

In order to examine the interaction between groundwater and surface water, a groundwater-monitoring network was established in September 2010 by installing twenty-two piezometers equipped with Odyssey data loggers at eight sites in the KRW (Figure 3). At each site, a bank piezometer was installed on both right and left banks of the stream in addition to the in-stream piezometer. The piezometers, measuring 1.9 cm by 3.0 m (0.75 in. by 10 ft.) with 44 holes at one end along with a welded drive tip, were inserted at various depths, depending on site conditions, using hand auger, slide hammer and high-reach iron auger (Figure 4). In addition, three piezometers in the One Island Lake area and one piezometer in the Mainstem sub-basin of the KRW (Figure 1) equipped with data loggers were installed in the summer of 2011. Each Odyssey™ data logger (Dataflow Systems Pty. Ltd.) was calibrated using a three-point calibration method before being inserted in the piezometer and was set to record the groundwater level at 20 minute intervals. The surface-water levels and discharge at each study

Table 1. Description of satellite imagery used in the mapping of land-use change.

Remotely sensed data	Year	Spectral resolution	Spatial resolution
Landsat 4 5 TM	1984, 2010	Multispectral (Bands 1 5 and 7)	30 m
Landsat 7 ETM+	1999	Multispectral (Bands 1 5 and 7)	30 m

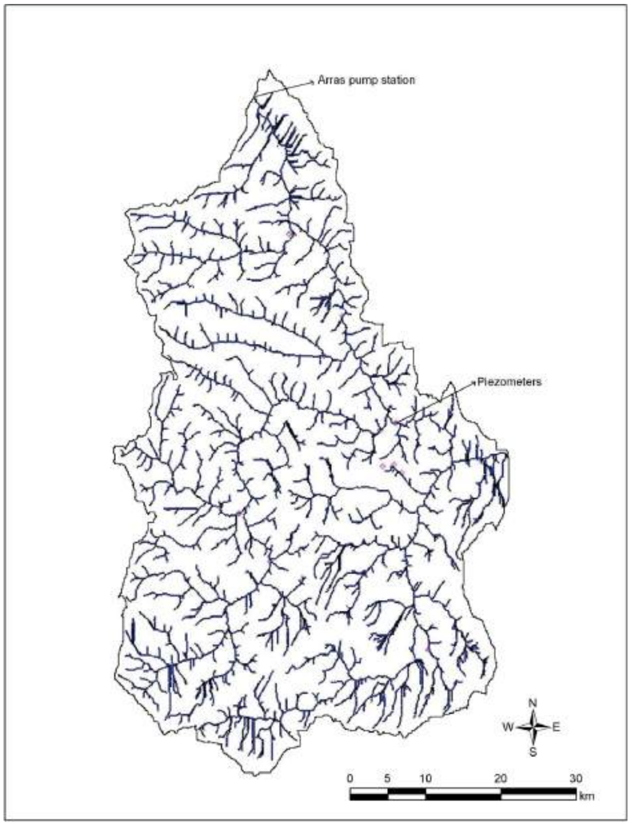

Figure 3. Study sites (red circles) with piezometers installed in the Kiskatinaw River watershed.

site were measured using staff gauges along with Odyssey capacitance data loggers and Sontek's FlowTracker® Acoustic Doppler Velocimeter. The cross-sections were completed in accordance with the British Columbia Hydrometric Standards (BC Ministry of Environment, 2009).

Results

Land-Use Change in the Kiskatinaw River Watershed

The land-use maps for 1984 and 2010 (Figure 5a, b) include the following feature classes:

- **Cropland** – all cultivated agricultural land
- **Coniferous forest** – forested land dominated by trees that remain green throughout the year
- **Deciduous forest** – forested land dominated by trees that lose their leaves at the end of the frost-free season
- **Mixed forest** – forested land in which neither coniferous nor deciduous type dominates over the other
- **Planted or regrowth forest** – small plants of both coniferous and deciduous types that have regrown or been planted after forest fire, clear cutting or any other decay event; this class may also include some herb-shrubs, as they are hard to differentiate during digital-image classification using imagery of 30 m resolution;
- **Forest-fire lands** – only the 2010 land-use map has a forest-fire feature class, since a fire event occurred in the KRW in 2006
- **Cut block** – forest cut-block areas that have been cleared for timber or any other purpose; this class includes most of the gas development infrastructure, such as drilling pads
- **Pasture lands** – grassland kept for feeding livestock and also used for agriculture
- **Water** – water channels and lakes, but most of the rivers and creeks could not be captured by imagery of 30 m resolution
- **Wetland** – marshes and swamps (both nonforested and slightly forested) where the water table is at, near or above the ground surface for a significant part of the year
- **Built-up area** – land covered by human-built structures (e.g., houses, businesses, roads and industrial infrastructure); structures less than 30 m in width or length could not be included in the land-use maps because of the 30 m maximum spatial resolution of the imagery

From the land-use maps shown in Figure 5, the overall change may not be very conspicuous for the entire watershed, but changes for a particular land-use type within particular sub-watersheds are significant. Figure 6a presents

Figure 4. Stages of piezometer installation in the Mainstem subbasin, Kiskatinaw River watershed.

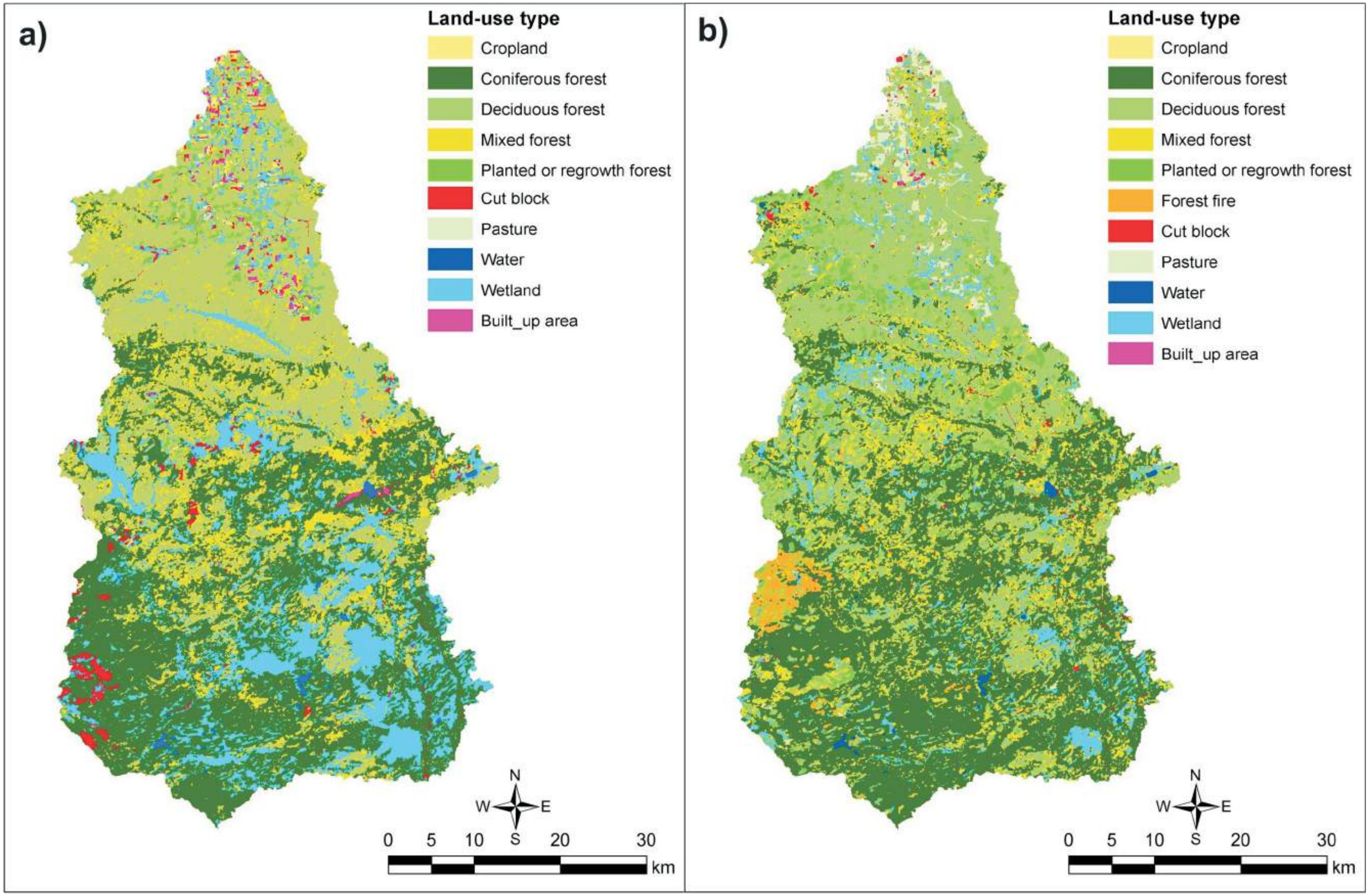

Figure 5. Land-use maps of the Kiskatinaw River watershed in **a)** 1984, and **b)** 2010.

the total area gained and lost for each land-use (LU) type between 1984 and 2010. In this figure, the area lost for a particular feature class was gained by other classes. For example, the substantial area of lost wetland (372 km^2) between 1984 and 2010 might have been added to other forest-type features. The change in the area of forest type is more or less consistent, although a higher gain of 144 km^2 in the area of planted/regrowth forest has been noted. The significant gain (48 km^2) in the area of forest fire refers to the ‘Hourglass Forest Fire’ in the KRW in 2006, which caused significant loss of forest stand in this watershed. The higher loss (21 km^2) than gain (4 km^2) in built-up area between 1984 and 2010 may be problematic and requires a review of the classification process. The probable cause of this is the low image quality in 1984 due to cloud cover over the study area, which caused uncertainty during the classification process. Figure 6b presents the net change for each land-use feature class between 1984 and 2010, with negative change in area indicating higher loss and positive change indicating higher gain of the land-use feature.

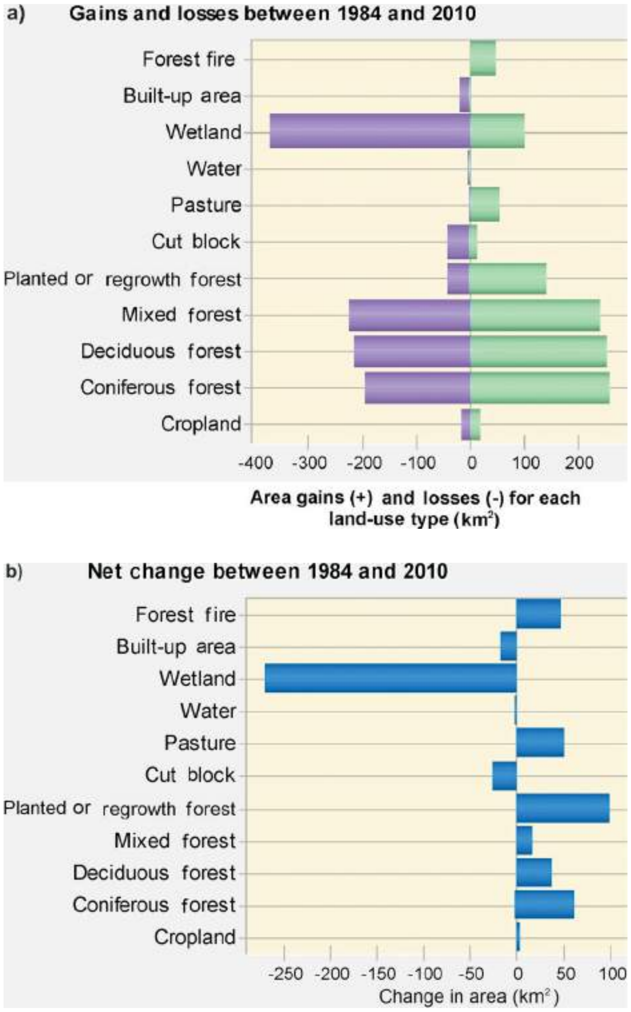

Figure 6. Land-use change between 1984 and 2010 in the Kiskatinaw River watershed: **a)** total gains and losses for each land-use type, **(b)** net change in area for each land-use type.

Direction of Regional Groundwater Flow

The direction of regional groundwater flow in the KRW was determined using GSSHA software (Downer, 2002) and based on observed groundwater-level data collected from the groundwater-monitoring network. As can be seen in Figure 7, the groundwater-flow pattern in the KRW is a through-flow system (i.e., groundwater passing through the stream network).

Groundwater Contribution to Stream Flow

The PART base-flow separation program of the USGS was used in this study to quantify groundwater contribution to surface water. This program estimates daily base flow by considering it to be equal to stream flow on days that fit a requirement of antecedent recession, and then linearly interpolating it for other days in the record (Rutledge, 1998). Groundwater (base-flow) contribution to stream flow in the KRW was examined for the period January 2007 to December 2011 (Figure 8). It can be seen that groundwater contributes significantly to the stream flow and that this contribution varies with time. The monthly mean stream flow in the KRW is shown in Figure 9. Comparing Figures 8 and 9 shows that the annual base-flow index (i.e., annual groundwater contribution to river flow) increases when the annual mean stream flow decreases, and vice versa. Table 2 lists

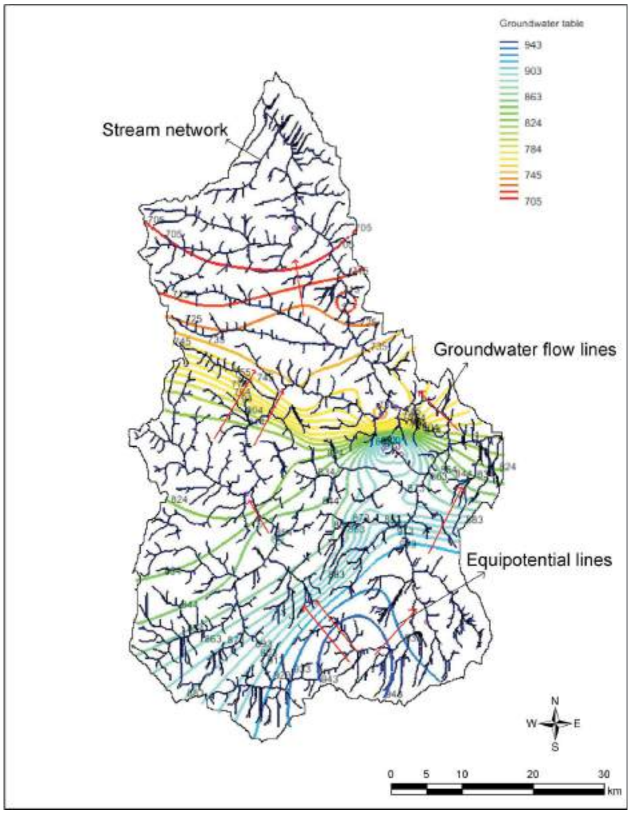

Figure 7. Groundwater table (m) in the Kiskatinaw River watershed.

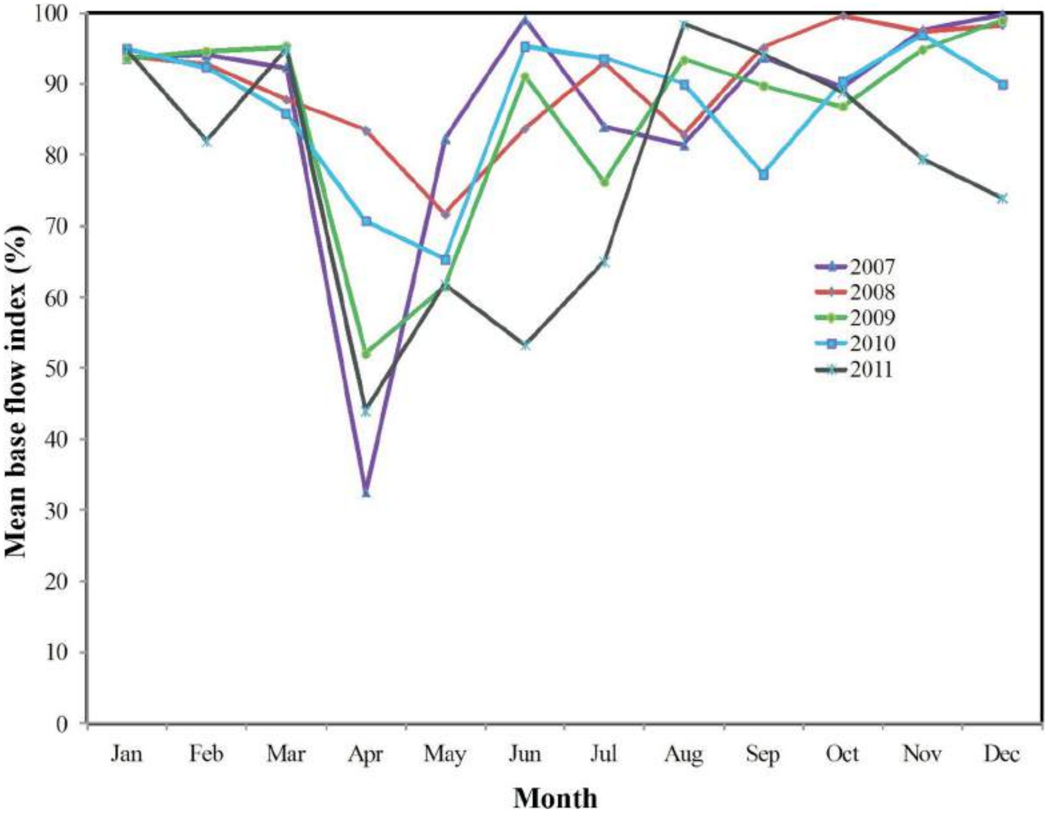

Figure 8. Base-flow index (groundwater contribution to river) in the Kiskatinaw River watershed.

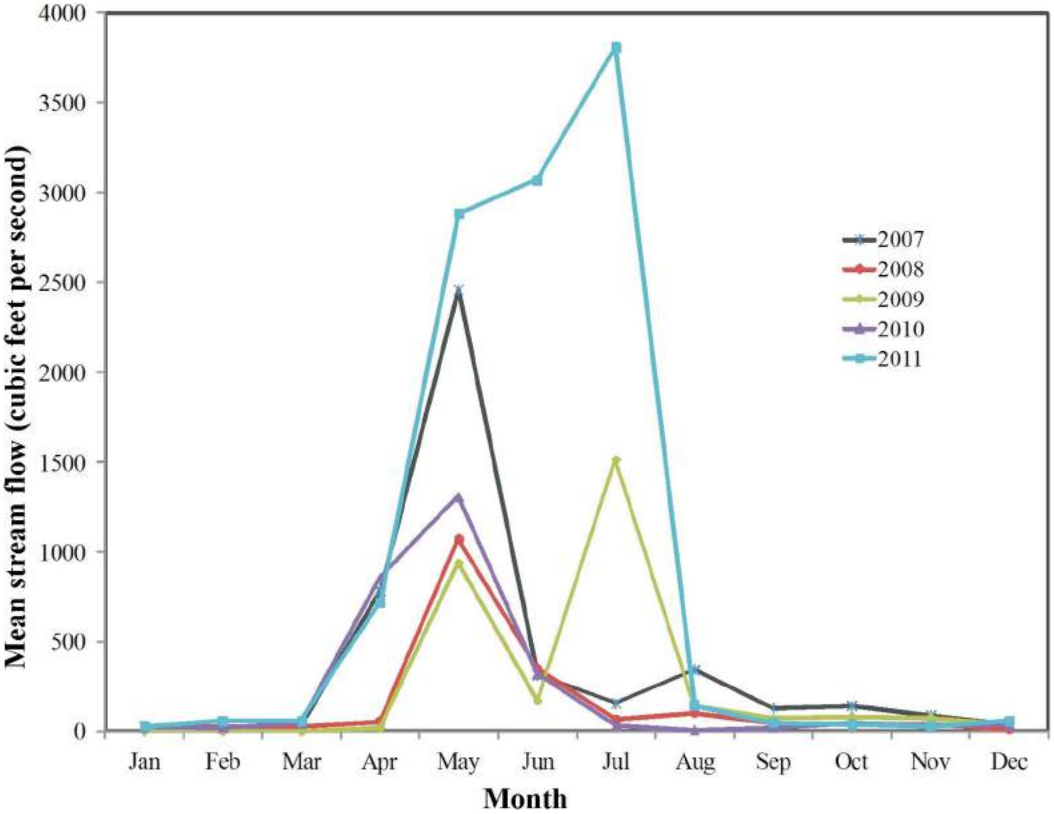

Figure 9. Monthly mean stream flow over time in the Kiskatinaw River watershed.

Table 2. Mean stream flow, mean base flow and base-flow index in the Kiskatinaw River watershed.

Year	Mean stream flow (cfs)	Mean base flow (cfs)	Base-flow Index (%)
2007	378.16	276.53	73.12
2008	156.09	117.27	75.13
2009	256.31	181.42	70.78
2010	230.01	163.1	70.91
2011	912.09	524.48	57.5

Abbreviation: cfs, cubic feet per second

the base-flow index in the KRW, with the highest index (75.13%) observed in the dry year (2008).

Conclusion

Land-use maps were generated by satellite-image analysis using remote-sensing and GIS tools to capture the land-use change dynamics within the Kiskatinaw River watershed (KRW). The gain and loss of 11 land-use features between 1984 and 2010 were quantified, and a significant land-use change was found for a number of features in the KRW. The digital-image classification has proven to be an effective method for land-use mapping, but some manual GIS editing was required to generate a more complete map because the Landsat imagery at 30 m spatial resolution was incapable of capturing features smaller than 30 m. Thus, a major part of the rivers and creeks, as well as the roads, could not be captured during the mapping effort.

The groundwater flow in the KRW was determined to be a through-flow system. Based on hydrograph separation results obtained using PART program, it was found that groundwater contributed a major part of the river flow in the KRW during the dry season and snowfall events. This contribution decreased during spring runoff and wet season, when surface runoff contributed a major part of the river flow. The annual base-flow index of the KRW increases when the annual mean stream flow decreases, and vice versa. Future work involves the development of a numerical model using gridded surface-subsurface hydrological analysis to quantify the combined impacts of land-use/land-cover and climate changes on groundwater–surface water interaction in the riparian zone of the KRW.

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