ECOHYDROLOGY
Ecohydrol. **4**, 315–321 (2011)
Published online 24 August 2010 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/eco.162

Effect of land cover change on runoff curve number estimation in Iowa, 1832–2001

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ABSTRACT

Within the first few decades of European-descended settlers arriving in Iowa, much of the land cover across the state was transformed from prairie and forest to farmland, patches of forest, and urbanized areas. Land cover change over the subsequent 126 years was minor in comparison. Between 1832 and 1859, the General Land Office conducted a survey of the State of Iowa to aid in the disbursement of land. In 1875, an illustrated atlas of the State of Iowa was published, and in 2001, the US Geological Survey National Land Cover Dataset was compiled. Using these three data resources for classifying land cover, the hydrologic impact of the land cover change at three points in time over a period of 132+ years is presented in terms of the effect on the area-weighted average curve number, a term commonly used to predict peak runoff from rainstorms. In the four watersheds studied, the area-weighted average curve number associated with the first 30 years of settlement increased from 61·4 to 77·8. State-wide mapped forest area over this same period decreased 19%. Over the next 126 years, the area-weighted average curve number decreased to 76·7, despite an additional forest area reduction of 60%. This suggests that degradation of aquatic resources (plants, fish, invertebrates, and habitat) arising from hydrologic alteration was likely to have been much higher during the 30 years of initial settlement than in the subsequent period of 126 years in which land cover changes resulted primarily from deforestation and urbanization. Published 2010. This article is a US Government work and is in the public domain in the USA.

KEY WORDS land usage; surface drainage; land surveys; history

Received 13 November 2009; Accepted 7 July 2010

INTRODUCTION

Conversion of tall grass prairie and forested landscapes to agricultural land in Iowa has driven aquatic habitat degradation and reduced biodiversity (Poole and Downing, 2004). These changes in land cover have altered streamflow and sediment supply (Randhir and Hawes, 2009). Altering the natural flow regimes is known to lead to deleterious effects on wetland and riparian vegetation, fish, benthic invertebrates, and aquatic habitats (Bunn and Arthington, 2002; Poff and Zimmerman, 2010). Changes in extreme sedimentation that occur during large storm events, but infrequently, allow aquatic organisms to rebound. However, chronic deposition of large volumes of sediment from smaller flow events can reduce aquatic biodiversity (Richter *et al.*, 1997), thereby limiting a system's ability to rebound after an extreme storm and sedimentation event (Farnsworth and Milliman, 2003). This investigation estimated differences in the runoff curve number, which provides an insight into changes in large streamflow events in Iowa under three historical land cover regimes to gain a better understanding of the ecohydrological implications of land cover change.

Land cover change in the first few decades of European-descended settlement in Iowa occurred at an astonishing rate. Between 1832 and 1859, prior to most settlement in Iowa, the General Land Office (GLO) conducted the first public land survey of the state. Surveyors traversed the state in a one-mile-by-one-mile grid describing identifiable markers, topography, soil type, water bodies and boundaries of land cover. In 1996, the land cover information from the GLO surveys for the State of Iowa was digitized (paper maps converted to digital maps) into a geographic information system for mapping analysis (Anderson, 1996).

Approximately three decades after settlement, entrepreneur A. T. Andreas began producing maps of counties in the Midwest. With success in Illinois and Minnesota, Andreas used the services of over 300 of his own employees over the course of approximately 15 months to 'compile the history, execute portraits, draw pictures of homes, farms, buildings and cities, and record faithfully the maps (including land cover) and plats of counties and towns (in Iowa)' (Andreas, 1875). Andreas' Illustrated Historical Atlas of the State of Iowa (IASI) was published in 1875 with nearly 23 000 subscribers. Prairie was the predominant land cover class in the GLO survey, however, in the IASI, prairie was not included as a land cover class, indicating that it was not found or that it was classified differently. The 2001 National Land Cover Dataset (NLCD 2001) (USGS, 2001) was developed to provide a consistently derived (from 30 m resolution multitemporal Landsat 5 and 7 imagery),

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public-domain land use product for the Nation (Homer *et al*., 2007) with land cover classification descriptions and methodology of the minimum 1-acre mapping unit described by Homer *et al*. (2004).

The Natural Resource Conservation Service (NRCS) runoff curve number (CN) method has been the foundation of the hydrology algorithms in many simulation models for hydrology, soil erosion, and nonpoint source water quality for over five decades. However, the method was originally developed only as an event-based model to predict peak streamflow, and the scientific basis of other uses has been questioned (Garen and Moore, 2005). The CN method converts mass rainfall into mass runoff using the empirically derived CN, which is a function of soil type, land cover, interception, and surface storage parameters (SCS, 1986). The generation of land cover and soil type maps, coupled with assumptions about interception and surface storage, make it possible to create maps of curve numbers for each land cover dataset.

Four watersheds were selected from the State of Iowa to provide an assessment of changes in Iowa's land cover and the corresponding curve number changes for the three land cover datasets. The watersheds are representative of the State in terms of climate, geology, hydrology, topography, soil type, and land cover. The four basins are the Skunk River, Turkey River, Floyd River, and West Nishnabotna River (Table I, Figure 1).

Table I. Case study watershed characteristics.

Watershed	Drainage area (km^2)	Mean channel slope (m/km)	Average annual precipitation (cm)
Turkey River	4408	0·66	89
Skunk River	11419	0·23	94
Floyd River	2313	0·52	70
West Nishnabotna River	4310	0·56	85

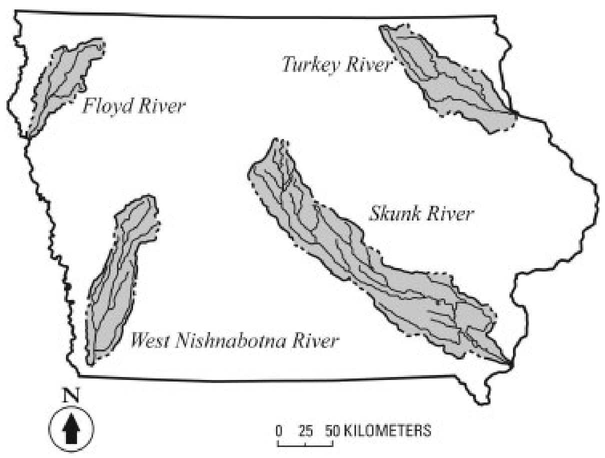

Figure 1. Case study watersheds in Iowa.

METHODS

The hand-drawn maps of the IASI were digitized and the land cover was classified as field, timber, marsh, lake, town, or transportation route. The GLO land cover map for Iowa was previously digitized by Anderson (1996) using 38 land cover classes, 27 of which are included in the four selected watersheds. The NLCD 2001 dataset is a digitized map product with 29 land cover classes, 10 of which are included in the study basins. Positional accuracy for these three datasets is difficult to quantify. Data-quality investigations suggest that the use of GLO surveys for small areas necessitate verification of positional accuracy of landscape features, but for large watershed areas, model reconstruction is not a critical area of concern (Wang, 2005). No analysis of positional accuracy was undertaken in this study on the IASI dataset. A national accuracy assessment of the NLCD 2001 has not formally been conducted, but accuracy assessment techniques have been developed for this particular product (Stehman *et al*., 2008). However, the NLCD 2001 cropland in Iowa, was compared to the 2002 US Department of Agriculture (USDA) Census for Agriculture and the difference in mapped cropland between the two sources was only 3·0% (Maxwell *et al*., 2008).

The 27 GLO, 6 IASI, and 10 NLCD 2001 land cover classifications along with their corresponding curve number designations are shown in Table II. Designations of curve numbers were made by comparing historical land cover class descriptions from the GLO (Anderson, 1996), IASI (Andreas, 1875), and NLCD 2001 (USGS, 2001) datasets to the Natural Resources Conservation Service (NRCS) curve number chart (USDA NRCS, 2005).

WinTR-55 is a computer program that generates hydrographs for single-events using a rainfall–runoff relation that incorporates the curve number to produce a peak streamflow response to rainfall (USDA NRCS, 2005). Curve number estimation using WinTR-55 (USDA NRCS, 2005) requires classifications of land cover, hydrologic soil group (HSG), treatment, and hydrologic condition. The HSG is a classification of soils having similar minimum infiltration rates (USDA NRCS, 2007a). Soils can be classified as 'A', 'B', 'C', 'D', or the dual classes of 'A/D', 'B/D', and 'C/D'. 'A' soils have the highest minimum infiltration rates and 'D' soils have the lowest minimum infiltration rates. The first letter in the dual class HSG is for drained areas and the second letter is for undrained areas. The HSG in this study was determined using the 21 component US General Soil Map (STATSGO) dataset (USDA NRCS, 2007b).

Although the HSG could have changed from 1875 to 2007, there is no way of estimating the historical HSG because there were no data collected on the minimum soil infiltration rate in the 1800s. Therefore, the modern designations provide the best information available for all three datasets. Treatment is a cover type modifier that describes

Table II. GLO, IASI and NLCD of 2001 land cover types and corresponding Natural Resources Conservation Service curve numbers by hydrologic soil group.

GLO	IASI	NLCD 2001	NRCS cover description	HSG A	HSG B	HSG C	HSG D
Barrens	—	Barren land	Woods–grass combo	32	58	72	79
Bayou	—	—	—	100	100	100	100
Brush	—	Shrub/scrub	Brush	30	48	65	73
City	—	—	Residential 1/8 acre	77	85	90	92
Drain	—	—	—	100	100	100	100
Field	Field	Cultivated crops	Straight row crops	67	78	85	89
Grove[a]	—	—	Woods	30	55	70	77
Lake	Lake	—	—	100	100	100	100
Marsh	Marsh	—	—	100	100	100	100
Meadow	—	Pasture	Meadow	30	58	71	78
Openings	—	—	Meadow	30	58	71	78
Pond	—	Open water	—	100	100	100	100
Prairie	—	—	Meadow	30	58	71	78
Prairie/timber	—	—	Woods–grass combo	32	58	72	79
Ravine	—	—	—	100	100	100	100
River (border)	—	—	—	100	100	100	100
Rough	—	—	Brush	30	48	65	73
Scattered trees[a]	—	—	Woods–grass combo	32	58	72	79
Slough	—	—	—	100	100	100	100
Spring	—	—	—	100	100	100	100
Swamp	—	—	—	100	100	100	100
Thicket[a]	—	—	Woods	30	55	70	77
Timber[a]	Timber[a]	Forest: deciduous, evergreen or mixed[a]	Woods	30	55	70	77
Timber/barrens[a]	—	—	Woods–grass combo	32	58	72	79
Timber/openings[a]	—	—	Woods–grass combo	32	58	72	79
Village	Town	Developed: low, medium or high intensity	Residential 1/2 acre	54	70	80	85
Wetland	—	Wetland: emergent, herbaceous, or woody	—	100	100	100	100
—	Transportation route	—	Dirt streets	72	82	87	89
—	—	Developed open space	Open space	39	61	74	80
—	—	Pasture/hay	Pasture/grassland	39	61	74	80

GLO, General Land Office survey; IASI, Andreas' Illustrated Historical Atlas of the State of Iowa; NLCD, National Land Cover Dataset.
—denotes no equivalent classification.
[a] A forest classification for this study.

the management of cultivated land. Treatment includes both mechanical and management practices of the soil, and was considered 'straight row' for all agricultural land cover classifications. Hydrologic condition indicates the effects of cover type and treatment on runoff and was considered 'good' for all land cover classifications. Curve number values of 100 indicate there is no infiltration (i.e. impervious land or standing water). Interception and surface storage terms in the CN method are lumped together as part of an initial abstraction term that varies by CN and has been studied extensively (Jiang, 2001), yet the original equation developed in the 1950s relating the initial abstraction and the curve number remains the only widely accepted approach. The area-weighted average curve number approach used in this analysis takes the CN computed for each combination of parameters and multiplies this CN value by its proportional watershed area, producing an area-weighted average CN for the watershed.

Because forested land was more difficult to convert into agricultural land than prairie, this study looked at the forest fraction within each watershed to see if a relation existed between forest fraction or forest fraction change and the area-weighted average curve number. To evaluate this relation, land cover for each dataset was divided into forested or non-forested categories. For the IASI and NLCD 2001, this designation was simple. In the IASI, one land cover class was forest and in the NLCD 2001, the evergreen, deciduous and mixed forest classes were defined as forest. The GLO dataset presented challenges because the delineation of some transitional land cover classes was not clearly defined. Anderson (1996) included descriptions and noted the ambiguity of some transitional land cover classes in the GLO survey. If transition forest land cover classes were unclear from these descriptions, the determination was made based on the class name. If a forest-related term was the first land cover word in the description, the land cover was classified as forest, but if it was the second word in the description then the land cover was not described as forest. This evaluation resulted in forest classifications of scattered trees, timber/barrens, and timber/openings, and a non-forest classification of prairie/timber. Timber, thicket, and grove were not transitional classes and were classified as forest land cover in the GLO survey.

RESULTS AND DISCUSSION

The GLO, IASI, and NLCD 2001 curve number maps for the four Iowa study watersheds are shown in Figures 2–4, respectively. Figure 5 shows the magnitude of change of the curve number between the GLO and IASI datasets for each watershed. Figure 6 shows the magnitude of change of the curve number between the IASI and NLCD 2001 datasets for each watershed. Negative values of change indicate that the land provides less direct runoff. The curve numbers are mapped such that high curve number values, representing a large proportion of direct runoff, are displayed in light colours, and low curve number values, representing a small proportion of direct runoff, are displayed in dark colours.

The area-weighted average curve numbers for each watershed, show a sharp increase between the GLO and IASI datasets, and a slight decrease between the IASI

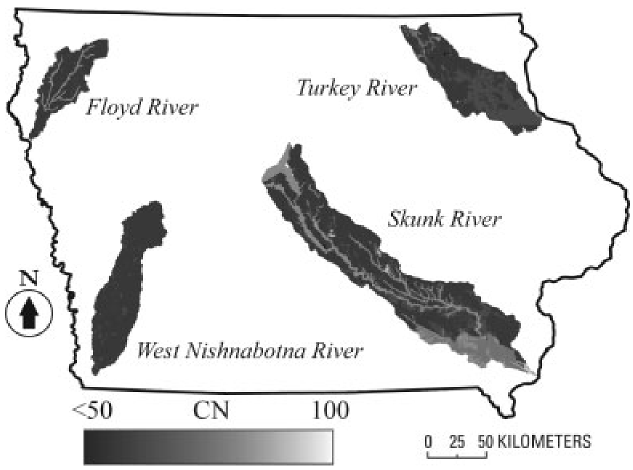

Figure 2. General Land Office survey (GLO) land cover based curve numbers for selected basins in Iowa.

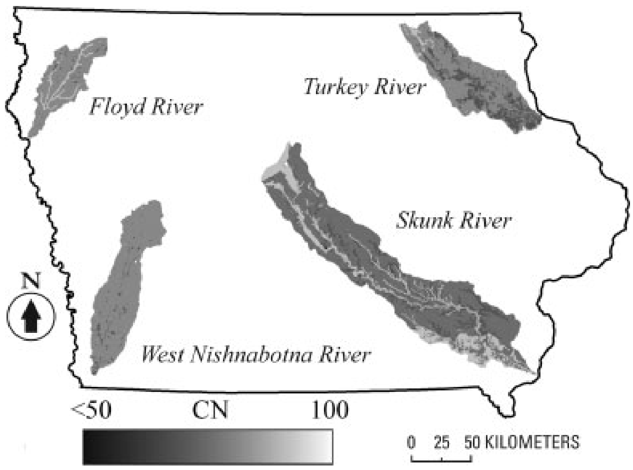

Figure 3. Andreas' Illustrated Historical Atlas of the State of Iowa (IASI) land cover-based curve numbers for selected basins in Iowa.

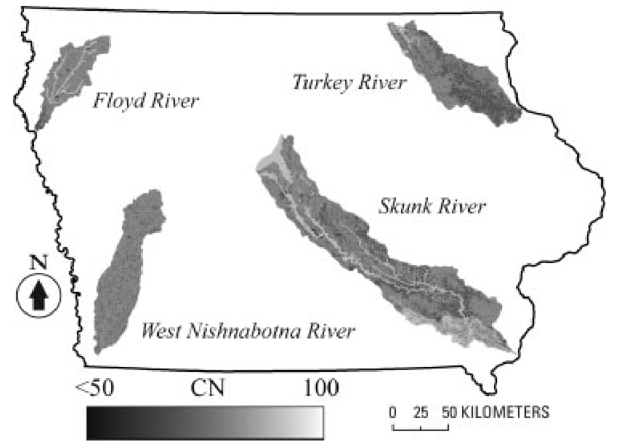

Figure 4. National Land Cover Dataset of 2001 (NLCD 2001) land cover-based curve numbers for selected basins on Iowa.

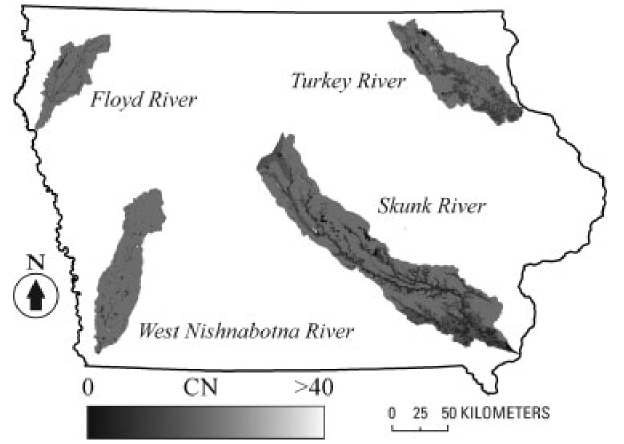

Figure 5. General Land Office survey-Andreas' Illustrated Historical Atlas of the State of Iowa (GLO-IASI) curve number change for selected basins on Iowa.

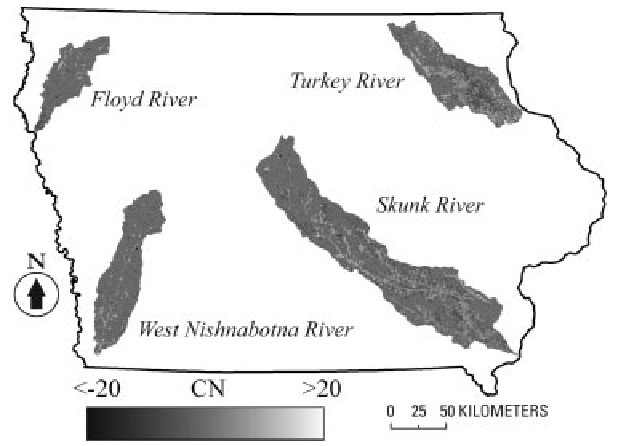

Figure 6. Andreas' Illustrated Historical Atlas of the State of Iowa-National Land Cover Dataset of 2001 (IASI-NLCD 2001) curve number change for selected basins on Iowa.

and NLCD 2001 datasets (Table III). The Floyd River and West Nishnabotna River have larger CN increases between the GLO and IASI datasets than the Skunk River and Turkey River. The forest fraction is greater in the Turkey River and Skunk River watersheds, resulting in smaller changes in the curve number between the GLO

Table III. Computed area-weighted average curve numbers and change between land cover classifications.

Watershed	GLO CN	Δ CN	IASI CN	Δ CN	NLCD 2001 CN
Turkey River	59·3	15·7	75·0	−1·1	73·9
Skunk River	63·5	15·2	78·7	−1·1	77·6
Floyd River	60·4	18·6	79·0	−1·2	77·8
West Nishnabotna River	58·2	19·4	77·6	−1·1	76·5
All four combined	61·4	16·4	77·8	−1·1	76·7

GLO, General Land Office survey; Δ, change; CN, Natural Resources Conservation Service curve number; IASI, Andreas' Illustrated Historical Atlas of the State of Iowa; NLCD 2001, National Land Cover Dataset of 2001.

Table IV. Percentage of watershed with a forested land cover and change between land cover classifications.

Watershed	GLO	Δ	IASI	Δ	NLCD 2001
Turkey River	43	−16	27	−13	14
Skunk River	22	−2	20	−13	7
Floyd River	0	0	0	1	1
West Nishnabotna River	2	2	4	−2	2
All four combined	20	−4	16	−9	7

GLO, General Land Office survey; Δ, change; CN, Natural Resources Conservation Service curve number; IASI, Andreas' Illustrated Historical Atlas of the State of Iowa; NLCD 2001, National Land Cover Dataset of 2001.

Table V. Computed forested areas, in hectares, and percent change between land cover classifications.

Watershed	GLO	Δ (%)	IASI	Δ (%)	NLCD 2001
Turkey River	191 160	−38	119 327	−50	60 149
Skunk River	251 058	−8	230 227	−64	83 067
Floyd River	311	100	0	N/A	1757
West Nishnabotna River	8858	83	16 168	−75	4005
All four combined	451 386	−19	365 721	−59	148 977

GLO, General Land Office survey; Δ, change; CN, Natural Resources Conservation Service curve number; IASI, Andreas' Illustrated Historical Atlas of the State of Iowa; NLCD 2001, National Land Cover Dataset of 2001.

and IASI datasets because forest was more difficult to convert to arable land than prairie (Table IV).

The GLO Turkey River watershed forest fraction was twice as large as the GLO Skunk River watershed forest fraction, and between the GLO and IASI datasets were deforested at a much higher rate. During this period, the forested area in the Skunk River watershed decreased 8%, whereas the forested area in the Turkey River decreased 38% (Table V), yet the curve number change between the two is similar. One might expect that a larger percentage of change in forested land cover would result in a greater increase in the curve number, but this is not observed between the Skunk River and Turkey River watersheds. Another observation is the 83% increase of the forest fraction in the West Nishnabotna River watershed between the GLO and IASI datasets; however, only 2% of watershed was classified as forested in the GLO. This increase in the forest fraction between the GLO and IASI datasets in the West Nishnabotna River is likely a function of different classification schemes between the two datasets.

The changes in the area-weighted average curve numbers for forested areas were relatively consistent across the four watersheds (Table VI). The area-weighted average CN in forested areas increased by an average of 6·1 between the GLO and IASI datasets, and the area-weighted average CN in forested areas decreased by an average of 0·9 between the IASI and NLCD 2001. These changes could indicate that during the time between the GLO and IASI datasets either (1) forest types with lower curve numbers were preferentially removed (possibly forests on land with higher minimum infiltration rates), (2) the classification scheme tends to underestimate the curve number in the GLO dataset, or (3) it is coincidental that the curve number change is around six for all four watersheds. The curve number change in forested areas between the IASI and NLCD 2001 is also consistent. This change could be a function of land use change across the State of Iowa combining deforestation in locations with soils with high minimum infiltration rates, and reforestation in locations with soils with low minimum infiltration rates (such as stream buffers in floodplains with high clay content).

The greatest area-weighted average curve number changes between the GLO and IASI datasets were in the West Nishnabotna River and Floyd River watersheds, both of which had larger fractions of prairie and smaller fractions of forest than the Turkey River and Skunk River watersheds of eastern Iowa. The area-weighted average curve number between the GLO and IASI datasets for the four study basins showed a combined increase of 16·4 from 61·4 to 77·8. The CN change between the IASI and NLCD 2001 datasets for all four watersheds showed a consistent decrease of about −1·1 to an area-weighted average of 76·7 despite the variability in the change of forested land cover between the watersheds.

To put the changes in the area-weighted average curve number in context of how the changes relate to peak streamflow response to rainfall is useful. Assuming a hypothetical basin with a 52 km^2 drainage area with the standard 24-h rainfall distribution of Des Moines County, Iowa, a 2% slope, and a hydraulic watershed length of 442 m yields a time of concentration (the amount of time it takes runoff generated from the most distant point in a watershed to reach the watershed outlet) of about 51 min using the Soil Conservation Service lag equation (USDA SCS, 1986). Table VII shows the flood frequency computation output from WinTR-55 (USDA NRCS, 2005) using the computed area-weighted average CNs of 61 (GLO), 77 (IASI), and 76 (NLCD 2001). In this example, the streamflow magnitude of the estimated 2-year return interval (50% change exceedance flood) increased 306% and the estimated 100-year return interval (1% change exceedance flood) increased 74%

Table VI. Computed area-weighted average curve numbers and curve number changes between land cover classifications in only the forested areas of each watershed.

Watershed	GLO CN	Δ CN	IASI CN	Δ CN	NLCD 2001 CN
Turkey River	60·0	6·0	66·0	−0·1	65·9
Skunk River	67·3	5·4	72·7	−0·7	72·0
Floyd River	72·8	N/A	N/A*	N/A	67·0
West Nishnabotna River	60·3	5·7	66·0	0·0	66·0
All four combined	64·1	6·1	70·2	−0·9	69·3

GLO, General Land Office survey; Δ, change; CN, Natural Resources Conservation Service curve number; IASI, Andreas' Illustrated Historical Atlas of the State of Iowa; NLCD 2001, National Land Cover Dataset of 2001; N/A, not applicable;
*, no land classified as forest.

Table VII. Flood frequency estimations (in m^3/s) for return intervals of a hypothetical basin located in central Iowa.

Land cover	CN	2-year	5-year	10-year	25-year	50-year	100-year
GLO	61	64	155	230	328	405	534
IASI	77	277	439	553	688	788	951
NLCD 2001	76	260	420	532	668	766	927

CN, Natural Resources Conservation Service curve number; GLO, General Land Office survey; IASI, Andreas' Illustrated Historical Atlas of the State of Iowa; NLCD 2001, National Land Cover Dataset of 2001.

between the GLO and IASI datasets. Between the IASI and NLCD 2001 datasets, the magnitude of the estimated 50% change exceedance flood decreased 6% and the estimated 1% change exceedance flood decreased 3%.

Land areas generating higher peak flows, represented by increases in the CN, were concentrated in the GLO to IASI timeframe when the land use conversion was from prairie and forest to agricultural fields. Averaging all four watersheds, continued deforestation and urbanization between the IASI and NLCD 2001 datasets did not result in increased peak flows. Figure 7 suggests that degradation of aquatic resources (plants, fish, invertebrates, and habitat) during the first three decades of European disturbance was substantially greater than any degradation caused by continued deforestation between 1875 and 2001.

Recent literature reviews by (Bunn and Arthington, 2002; Poff and Zimmerman, 2010) provide ample evidence for the important role played by hydrologic alteration in changing the physical and biological condition

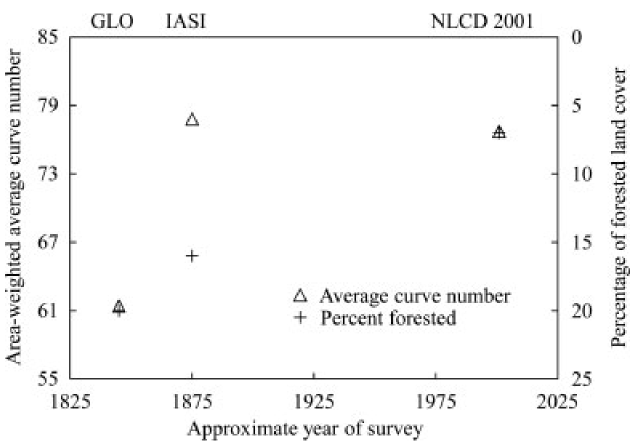

Figure 7. Average curve number and percentage of forested land cover.

of streams. The flow regime interacts with local geology and land forms to determine the amount and types of instream and riparian habitats that are present. Consequently, altering the magnitude and frequency of high flows coupled with increasing sources of sediment leads to dramatic changes in the types of habitats available to plants and animals, and changes the types of species that can live in these habitats and their abundances. Loss of habitat complexity leads to decreases in fish richness and assemblage structure. Reductions in stream bed stability and rapid changes in flow (higher magnitude, more frequently occurring) can lead to catastrophic downstream drift of benthic invertebrates, and the loss of species richness and diversity. Organism survival during floods is dictated primarily by shear stress, velocity, and turbidity.

The life history strategies of aquatic plant and animal species are adapted to natural flow regimes and alteration of these regimes can lead to the loss of native species and facilitate the spread of invasive species. Higher peak flows can also increase channel incision and reduce the frequency and duration of floodplain flooding, which can adversely affect plant and animal species that use these areas for spawning, feeding, and as nurseries. Changes in riparian and floodplain vegetation can also alter detrital inputs to the stream channel and change the way energy flows in these systems. Energy flows in these systems can also be altered by reductions in light penetration associated with increases in turbidity.

The analysis presented for the hypothetical basin in Table VII illustrates the magnitude of the changes that have occurred. A peak discharge prior to European disturbance of ∼400 m^3/s occurred on average only once every 25 years. By 1875, the same flow occurred on average once every 5 years. This fivefold increase in the frequency of high flow events indicates the magnitude of the hydrologic disturbance that has occurred in these systems, particularly during the early years of settlement.

CONCLUSIONS

In conclusion, and acknowledging the inherent uncertainty in the historical land cover datasets, land cover change in Iowa during the first three decades of European disturbance represents nearly all of the change in the area-weighted curve number in the period of 132+ years between the GLO survey (1832–1859) and 2001. The GLO to IASI alteration of the land cover significantly changed the peak streamflow response to rainfall. The area-weighted average curve number maps in Figures 2–6 provide a qualitative view of how land use affected model-estimated peak runoff before and after three decades of European disturbance, and in following 126 years.

Alteration of the natural hydrologic regime has undoubtedly contributed to the loss in diversity and habitat that has occurred in Iowa streams (Poole and Downing, 2004). Given the relatively small change in CN between 1875 and the present, it seems likely that much of the alteration of habitat and biological communities that has occurred as a result of hydrologic change occurred prior to 1875.

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