Expansion of Invasive Carp Range in Minnesota: Using Glacial Geomorphology, Digital Elevation Models and Vector Data to Identify Potential Watershed Breaches in ArcGIS

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Executive summary

Black, bighead, silver and grass carp (collectively referred to here as invasive carp) present a risk to ecosystem health, functionality, and value in Minnesota’s lakes, rivers and streams. Invasive carp will be able to access to most, but not all, Minnesota watersheds by swimming along river channels. Some watersheds have low susceptibility to invasive carp migration either because they are not tributaries to the Mississippi River or because fish passage is impeded by dams. Nonetheless, it may be possible for invasive carp to migrate into these otherwise inaccessible watersheds by swimming through hydrologic connections that link watersheds in headwater areas. This situation is referred to as a breach. This project provides insights and methodology for remote identification of potential breach sites using a geographic information system (GIS). Work presented here addresses point 2.5 of the Asian Carp Action Plan for Minnesota (Ad Hoc Asian Carp Task Force, 2011).

To identify potential breaches, sites of known hydrologic connectivity in the headwaters of the Des Moines and Minnesota Rivers were studied using widely-available GIS products (Figure 1). Similar features were identified in the Rush River watershed. In the Des Moines and Minnesota, potential breach sites are associated with glacial landforms. The Rush has lower topographic relief than the Des Moines headwaters and linear glacial depressions are not as well-defined as in the other two watersheds. Accordingly, watershed breaches may occur in a different topographic setting in this watershed: near low-relief prairie potholes, landforms which are known to have temporary surficial hydrologic connections (Rosenberry and Winter, 1997). This project also proposes methods to identify culverts and other infrastructure potentially critical to preventing watershed breaches.

Results underscore the important role hydrologic infrastructure like culverts, ditches and lake level control structures play in preventing breaches. Differences in glacial history and topographic relief in three of Minnesota’s watersheds produce different types of potential breach sites. The workflow described here is relatively simple, and can be used to identify potential breach sites in other Minnesota watersheds by workers with basic ArcGIS skills. However, this is not an exhaustive method: it cannot identify all potential breach sites, and it does not promise that the potential breach sites identified will necessarily become problematic. The success of this method depends on other efforts to verify hydrologic connectivity across watersheds and measure the likelihood that breaches occur at identified sites.

Please contact the author for shapefiles or other GIS data used in this project: bevisma@gmail.com
This study is based on three watersheds: The Minnesota River headwaters on Minnesota’s western border, the Des Moines headwaters in southeast Minnesota, and the Rush in south central Minnesota. The Des Moines headwaters are located on the steep flanks of the Coteau des Prairies; the Minnesota River headwaters and the Rush have lower topographic relief.

Objectives

This study uses GIS tools to find potential breach sites in the Rush River watershed. While these sites may be useful in their own right, the larger goal of the project is to provide methods and insights that can be used to identify potential breach sites throughout Minnesota. Objectives are as follows:

1. Identify potential breach sites in the Rush that are similar to known locations of hydrologic connectivity in other watersheds.
2. Search for other potential breach sites in Rush watershed.
3. Discuss breaches to aid future identification efforts in other watersheds.

The methods used here require access to ArcGIS, basic ArcGIS skills and licenses for the Spatial Analyst and 3D Analyst toolboxes.
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Introduction: Invasive carp and Minnesota’s surface waters

The bighead carp, silver carp, black carp, and grass carp (Hypophthalmichthys nobilis, Hypophthalmichthys molitrix, Mylopharyngodon piceus, and Ctenopharyngodon idella) are native to eastern Asia, and as invasive species in North America, have the potential to cause extensive and irreversible changes to aquatic habitats (DNR, 2007). Each of the four species has distinctive life history, breeding and feeding habits and present unique threats to native aquatic species, but they also share many similarities. Invasive carp are voracious consumers of plankton and were brought to the United States for use in wastewater treatment and aquaculture beginning in the 1960s (Chapman, 2010). The fish live in large rivers and are most active at high flows, which trigger spawning (DeGrandchamp et al., 2008). Invasive carp can produce millions of eggs a year (Chapman, 2010). In the carp’s native environment, mean annual air temperatures range from -6 to 25 degrees C, a wide temperature range which extends from southern Mexico to Hudson Bay in North America (Mandrak and Cudmore, 2004).

Fish escaped from captivity in Alabama and Arkansas soon after arrival and have swum up the Ohio, Mississippi and Missouri Rivers (Fishpro, 2004). Bighead and silver carp populations are increasing exponentially in the lower Mississippi River and are extremely abundant in some parts of the Mississippi River basin (Kolar et al., 2005). Grass carp have already become widespread throughout the contiguous US (Fishpro, 2004). Bighead carp are documented to have travelled 80km upstream in single high-water events (Kolar et al., 2005). Individuals have been found in the Mississippi River as far north as the Twin Cities metro area (DNR 2014). Suitable ecological niches for invasive carp exist throughout the entirety of Minnesota (DeVaney et al., 2009). Tributaries of the Mississippi River including the St. Croix and Minnesota Rivers provide carp with uninhibited migration routes.

Like other non-native species, invasive carp compete with native fish, but invasive carp are particularly harmful because they are fecund and abundant (Irons et al., 2007). When ecosystems are fundamentally altered by invasive species the value of ecological services lost can be very high (Pejchar and Mooney, 2009). River ecosystems are especially sensitive to invasive species because they are highly interconnected (Junk et al., 1989). Minnesota’s waters are no exception.

The Minnesota Department of Natural Resources (DNR) identified invasive carp as a potent threat to Minnesota’s native ecosystems, fisheries and recreation economy as early as the 1990s (DNR, 2007). The DNR (and other agencies) are trying to stop the advance of invasive carp in many ways (Ad Hoc Asian Carp Task Force, 2011). Unfortunately, if the history of other aquatic invasive species is any indication, it may be more prudent to assume that the arrival of invasive carp in Minnesota is inevitable.
(DNR, 2007). Some efforts focus on preparing for the arrival of invasive carp should efforts to stop their advance fail (Ad Hoc Asian Carp Task Force, 2011).

Since 2012, Minnesota DNR regional fisheries managers have been identifying potential breach sites. An early result of these ongoing efforts is a map illustrating the likelihood of carp migration into watersheds throughout the state (Figure 2). High dams, such as the Rapidan Dam on the Blue Earth River or the Byllesby Dam on the Cannon, are impassable to fish, so they protect upstream waters from invasive carp migration. Other rivers in Minnesota, like the Red and St. Louis, are not tributaries of the Mississippi, so invasive carp have no clear entry through surface waters. However, the complicated, interconnected surface water hydrology of Minnesota’s glacial and agricultural landscape may allow fish to migrate by other routes into otherwise inaccessible watersheds. One important way to prepare for the potential arrival of invasive carp is to ensure that upstream watershed breaches do not allow this to happen. So far, a watershed breach in Minnesota is a hypothetical situation. A breach requires hydrologic connectivity across a watershed divide, a situation that seems to be at odds with the definition of a watershed divide. However, such situations have been documented in the headwaters of the Minnesota, Red and Des Moines rivers.
Figure 2: A map showing previous efforts by the DNR to characterize risk of invasive carp migration through Minnesota. This project aims to improve understanding of the previously identified problems (DNR, 2013).
Background: The glacial, hydrologic and human landscape of potential breach sites

A basic understanding for the way glaciers shaped Minnesota’s landscape may help frame the topography and hydrology of central and southwest Minnesota. Until about 10 thousand years ago, the Laurentide ice sheet covered Minnesota in up to one mile of ice (Ojakangas and Matsch, 1982). The final advance of the ice sheet extended down to Des Moines, Iowa, but the Coteau Des Prairies – a high ridge in southwestern Minnesota – remained unglaciated (Lusardi, 1997). The margin of the glacier paused while situated on the flanks of the Coteau, in the headwaters of the modern Des Moines River. Glacial ice continued to move forward behind the relatively stationary margin, piling up rocky debris into a landform known as the Bemis terminal moraine. Subglacial channels carried meltwater out from under the ice to the front of the glacier, forming sub-linear valleys parallel to the direction of ice flow called tunnel valleys. Pauses in subsequent retreat from the Bemis moraine formed smaller parallel recessional moraines. Outwash channels between the moraines carried meltwater and debris away to the south. In some places the moraines were breached by glacial meltwater spilling to the southwest from ponds at the toe of the retreating glacier (Ojakangas and Matsch, 1982).

The modern Des Moines flows south out of Minnesota and joins the Mississippi at Iowa’s southeastern corner. The headwaters of the Des Moines River are at the front lines of potential watershed breaches because invasive carp have been documented downstream in Iowa. In this watershed the DNR has identified potential breach sites in five locations where water is known to move between watersheds (Figure 3; from Frohnauer, private communication). In two examples, ditches create permanent connectivity across watershed divides (points 10 and 1A; not shown). At the other sites, connections are temporary and only exist during high water (points 1C, 2, 3 and 4). In one example, common carp swam through drain tile across a watershed divide (point 3).

While artificial drainage has promoted connectivity at many of the sites in the Des Moines, connectivity at all the sites occurs in ancient glacial channels (Figure 3). The permanent connection at point 10 lies in the valley of an outwash channel where it crosses an older moraine. The temporary connections at points 1C, 2, 3 and 4 also lie in the bottom of outwash channels. Points 1C and 3 are in channels between nested moraines, while point 2 is in a large outwash channel that once drained proglacial meltwater to the south. Point 4 is in an outwash channel as well, and may be a site where proglacial lakes breached the Bemis moraine to flow to the southwest. Potential breaches occur where
modern streams interact with ancient meltwater channels in the disorganized topography of this high-relief watershed.

Figure 3: Temporary hydrologic connectivity across watershed divides has been observed in the headwaters of the Des Moines River where glacial outwash channels and tunnel valleys cross watershed divides.
The second example of known hydrologic connectivity across watershed divides comes from the headwaters of the Red and Minnesota Rivers. As glaciers retreated at the end of the last ice age, glacial meltwater created Lake Agassiz behind the Big Stone moraine near present-day Ortonville, MN on the Minnesota-South Dakota border (Upham, 1890). Glacial lake Agassiz had many outlets over the course of its existence, including to the south down the course of the present-day Minnesota River. Huge volumes of water drained along this route, eroding through up to 60m of till, forming the valley of the modern Minnesota River and profoundly influencing tributaries to this day (Fischer, 2003; Match, 1983; Gran et al., 2009). Presently, two rivers occupy the glacial River Warren channel near Ortonville. The Red River flows north, draining the bed of glacial Lake Agassiz; and the Minnesota flows southeast to the Mississippi in the valley left by River Warren. The DNR has identified the headwaters of the Red and Minnesota Rivers as a potential breach site (Frohnauer, private communication).

The headwaters of these rivers are particularly vulnerable to a breach because the rivers flow within the same paleochannel: the modern hydrology of this watershed divide is inset within the larger, older channel of glacial River Warren. The important lesson from the headwaters of the Minnesota, Red and Des Moines is that fundamentally, hydrologic connectivity exists in places where modern watershed divides cross older glacial channels.

Figure 4: The divide between the headwaters of the Minnesota and the Bois de Sioux Rivers originate in the same glacial outwash channel.
At first glance, the Rush is much flatter than the Des Moines headwaters (Figure 5). While there are a few tunnel valleys that terminate close to the northern boundary, they have lower relief than tunnel valleys in the Des Moines. The landscape of the Rush was formed by different glacial processes than the Des Moines (Jennings, 2007). When the Laurentide ice sheet melted away from south-central Minnesota, it left behind a ground moraine, characterized by dense clay-rich sediments arranged in low hills and swales. (Hobbs and Goebel, 1982).

![Figure 5: The Rush River watershed.](image)

Initially, river drainage networks were poorly established on the young, flat landscape and the ground moraine was covered in disconnected, ephemeral ponds. To ecologists, these closed depressions are known as prairie potholes. The prairie pothole region extends throughout much of the area covered by the Laurentide ice sheet (Johnson et al., 2004). The low relief and low hydrologic conductivity of glacial till means that prairie potholes have complex hydrology (Rosenberry and Winter, 1997). Surface water on unaltered prairie pothole landscapes is highly connected during wet times (Winter and LaBaugh 2003). Water infiltration rates are low in the clay-rich glacial tills, so precipitation fills the potholes until they overflow into adjacent basins in wet seasons (Leibowitz and Vining, 2003). When it is dry, water slowly drains away through the till or evaporates. Prairie potholes can change seasonally from aquifer recharge to discharge zones depending on fluctuations in water table height (Hubbard and Linder, 1986).
Today, over 80% of the land surface of parts of the Minnesota River basin is devoted to agriculture (Fry et al., 2011). The rich glacial soils and flat landscape are ideal for row-crop agriculture, but the seasonal wetlands are not. Minnesota’s hydrology has been dramatically altered in order to improve agricultural conditions (Blann et al., 2009). In watersheds surrounding the Rush, drained wetlands make up 12-18% of total watershed area (Schottler et al., 2012). To connect closed depressions to river systems, waterways have been lengthened by 20% or more (Lenhart et al., 2012). While artificial drainage channels provide outlets from potholes and thus may reduce the likelihood that a pothole basin will fill and overflow to adjacent basins, the artificial waterways themselves create permanent hydrologic connections.

It is possible that potential breaches in the low-relief Rush take a different form than the sites of watershed connectivity in the Des Moines, Minnesota, and Red River headwaters. In the other watersheds, artificial drainage appears to promote watershed connectivity by carrying water down ancient channels that often cross modern watershed divides. In the Rush, artificial drainage carries water away from potholes where channels never existed, so may discourage watershed connectivity. Altered or unaltered, highly-interconnected surface water hydrology may make Minnesota particularly vulnerable to aquatic invasive species like invasive carp.
Methods

This project used data from many sources. The first step is to collect or produce the required data. More information about data or tools referred to below is given in the GIS resources section at the end of this paper.

1) Obtain a statewide 30m-resolution DEM and hillshade from the Minnesota Geospatial Information Office.

   To help clearly illustrate topography while searching for potential breach sites, digital elevation model symbolization should have many distinct color breaks and be based on display extent (Figure 1). Digital elevation models should be made approximately 30% transparent and projected onto hillshades.

2) Obtain a local 3m-resolution DEM and hillshade from the DNR’s TopoViewer or the Minnesota Geospatial Information Office.

3) Obtain recent, high-resolution aerial images for the area from the Farm Service Administration National Aerial Imaging Program.

4) Obtain manually-delineated watershed divides at the HUC-10 level from the DNR’s DataDeli.

5) From the Minnesota DNR’s data deli, obtain stream channels that were originally hand-drawn for 1:24,000 scale maps.

6) Obtain wetlands from the National Wetland Inventory and lakes from the National Hydrology Dataset (there are more wetlands in this layer than in the DNR version).

7) Create a Topographic Position Index (TPI) layer for the area. The TPI layer created for this project was based on a 3m DEM and used a round window of 3 cell radius.

8) Create a topographically-delineated watershed divide from the 3m DEM using tools in the ArcGIS hydrology toolbox.

   When converting the flow accumulation raster into a stream network, choose a value with which to threshold the flow accumulation file such that the topographically-delineated stream network approximately matches the DNR’s manually delineated stream network. This will make the topographically-delineated stream network best represent actual hydrologic conditions.

9) Create a topographically-delineated flow accumulation network from the 3m DEM using tools in the ArcGIS hydrology toolbox.
Subsequent steps to find potential breach sites are described in the following paragraphs and are shown graphically in a flowchart (Figure 6). Use the 30m resolution DEM and hillshade to identify glacial lineations in and around the Rush watershed. Next, use the higher-resolution data to manually identify potential breach sites in the outwash channels and elsewhere. Mark the lowest point on divides that cross linear glacial depressions; these are potential breach sites. Low points should be easily identified visually with properly projected data, but the cross section tool in the ArcGIS 3D Analyst toolbar may help to find them, or to help to interpret terrain elsewhere. Municipal ditches are clearly visible on aerial photos and topographic data when displayed as described above, but the TPI layer may be useful to identify smaller ditch features, if any are present. Make note of any places where ditches cross divides: these are potential breach sites. Finally, manually inspect wetlands, potholes and lakes within 100m the divide. These features should easily be identified from topographic data and aerial images but the vector data may help as well. Of particular interest are potholes and wetlands without clearly-defined drainage channels. If any exist close to the divide, the lowest point of the divide where it runs adjacent to the depressions is a potential breach point: mark it. Inspect lake outlets for dams and mark them. The water level of many large lakes in the state is controlled; if control of the lake level is lost in an extreme event, the lake could overflow into another watershed potentially causing a breach.

Potentially critical culverts or other drainage infrastructure can be identified using the DNR 1:24k stream lines and the topography-based watersheds divides you created. Find intersections between these two features, then follow the ditch or stream downstream to the nearest culvert or bridge: mark these sites (assume that a culvert exists at every location where a road crosses a ditch).

In the Rush watershed, there is no rigid length scale to define the phrase “close to the divide.” Rather, professional discretion was used to decide which wetlands, lakes or ditches were of concern. Ditch or channel headwaters near potential breach sites are within 60 to 200 meters of the Rush River watershed boundary. Similarly, there is no size threshold that determines if a lake or wetland is of concern or not. On the Rush, the size of lakes and wetlands associated with potential breach sites range from almost 500 acres to 14 acres.
1. Glacial features

- 30m DEM
  Identify tunnel valleys, outwash channels or nested moraines

- 3m DEM
  Identify lowest or most likely breach point

2. Wetlands, lakes potholes near depressions *(3m or higher resolution data)*

- Are wetlands or potholes ditched?
  - YES
    - Across divide?
      - YES
        - mark site
      - NO
        - mark lowest point on divide
  - NO
    - mark lowest point on divide

3. Potentially critical culverts *(3m or higher resolution data)*

- Intersect DNR stream lines with topographically-delineated watershed divides.
- Find first culvert downstream from intersections.

4. Permanent hydrologic connections and potentially critical levees

- Do ditches cross divides?
  - YES
    - is the divide accurate?
      - YES
        - mark site
      - NO
        - Is it clear how to correct divide, and is the ditch contained within a single watershed?
          - YES
            - not of concern
          - NO
            - mark site
  - NO
    - Is there a wetland on one side of the divide and a ditch approaching from the other side?
      - YES
        - mark; potentially important levee
      - NO
        - not of concern

Figure 6: Flowchart shows steps used to remotely identify potential watershed breaches.
Results

This project identified two tunnel valleys crossing the Rush watershed orthogonally, two areas where unditched potholes exist close to the divide, and close to ten places where failure of drainage infrastructure could lead to hydrologic connectivity (Figure 7). The following is a brief summary of each site identified in the Rush and a description of the methods used. Discussion of each point proceeds counterclockwise around the watershed starting from point 6.

Figure 7: Overview of potential breach points in the Rush River watershed.
Point 6:

This point is in an area where the watershed divide crosses a chain of lakes (Figure 8). This particular point is a low spot along the divide, and also has the most hydrologic complexity in the area including proximity to ditches, roads and wetlands (Figure 9). To maintain hydrologic separation in this chain of lakes, it is important to maintain drainage away from the divide. Drainage appears to be achieved by ditch systems to the northeast of the potential breach point and to the south of the lakes within the Rush River watershed. The road berm to the southeast of point 6 may also be integral to preventing a breach.

Figure 8: 30m resolution digital elevation model (DEM) illustrates SSE-trending tunnel valleys crossing the Rush River watershed boundary.
Points 1, 11, 12:

These points border a wetland complex near the watershed divide that is surrounded by drainage ditches (Figure 10). This configuration may not necessarily be a problem, but in this case, the potential for a breach may be increased because the wetland complex occupies the bottom of a tunnel valley that trends orthogonal to the watershed divide (Figure 8). The ancient lowlands of the tunnel valley may enhance the potential for hydrologic connectivity across the modern divide, particularly in wet conditions.

A high-resolution DEM was used to identify potential breach point locations and to investigate sites along other glacial features in the image. The differences between the DNR and topographically-delineated watershed divides help to illustrate the complicated hydrology in this area.

Point 12 is the site of a potentially critical culvert. The potential for watershed connectivity at this site could be reduced by maintaining drainage from the wetland to High Island Creek watershed to the north. It would be prudent to ensure that there are no culverts connecting the wetland to the Rush (e.g., near points 1 and 11, which are potentially critical berms). If field work confirms connectivity to High Island at point 12 and no connectivity to the Rush, overall likelihood of a breach here is believed to be low.
Figure 10: A high-resolution digital elevation model shows the wetland positioned in the bottom of a linear depression that extends across the Rush watershed divide.
Point 2:

Point two is located in an area of low topographic relief (Figure 7). Initially, the point was of concern because ditches are visible close to the divide (Figure 11). While ditches close to divides can increase potential breach likelihood in steeper terrain, here they define drainage in an otherwise interconnected hydrologic landscape. Furthermore, the potholes on either side of the divide have small catchments (Figure 11A). This means that even if the potholes were not ditched, they would take a lot of rain to fill. Because it would take a ditch failure in addition to a lot of precipitation to cause watershed connectivity in this location, overall likelihood of a breach here is believed to be low.

Figure 11: Potential breach point 2. Inset (A) shows pothole catchment areas.
Points 7, 8, 9, 14 and 15:

These points are along the border of a large difference between topographically-delineated watersheds and the DNR watersheds. This situation implies the area has very low relief and once may have been hydrologically interconnected. Today, the boundaries of this nearly 10-square-mile area are dependent on functional drainage infrastructure (Figure 12). Discharge from the entire area flows through a single culvert at point A in Figure 12. Point 7 is the point at which water would breach the watershed divide if that culvert failed. The hydrology of this site is clearly highly altered, and hydrologic separation depends entirely on maintenance of artificial drainage and levees. The chance of hydrologic connectivity thus depends on the level of confidence we have in the entities responsible for ditch and culvert maintenance.

At Point 9, a topographically-delineated flow accumulation line crosses the DNR watershed divide. This may indicate that the DNR divide is inaccurate, and does not necessarily indicate a potential breach site. At points 8, 14 and 15 the situation is similar. These are a series of potholes along the divide (Figure 13). Because the potholes lack surficial drainage channels, it is unclear how well they drain, making them potential breach points. More work to define the likelihood of potential breaches in this area could take the form of hydrologic modeling, field work, or use of firsthand knowledge or aerial photos to identify past wet conditions.
Figure 12: The topographic position index clearly shows the extensive ditch network in the vicinity of points 7, 8, 9, 14, and 15. Here, topographically-delineated watershed divides are different than manually-delineated divides from the DNR, and topographically-delineated streams differ from the ditch network. Without artificial drainage on this low-relief landscape surface waters would likely be highly connected, though it is not clear if connectivity would extend across watershed divides. Circle at point A marks one culvert critical to maintaining the divide in this area.

Figure 13: Unditched basins near the divide are visible on a DEM.
Point 3:

Point three is of concern because a lakeshore forms the watershed boundary. This is an odd situation that may imply hydrologic connectivity prior to human modification. A topographic cross section shows that the south shore of Clear Lake is defined by a 1m-high berm (Figure 14 inset). Flowlines delineated from an unaltered 3m-resolution DEM indicate that the southern shore is lower than a road under which the artificial outlet passes (point A in Figure 14). If the culvert under this road is blocked, Clear Lake will flow south to the Minnesota River through Huelskamp Creek. Hydrologic connectivity at this site depends on maintenance of the berm at the south end of Clear Lake, keeping the culvert open to maintain lake discharge to the east, and to a lesser extent, keeping the small culvert open under County Hwy 1 to the south (point B in Figure 14).

Figure 14: Potential breach point 3, the southern end of Clear Lake. Pink lines are water flowlines delineated from unaltered 3m-resolution DEM. Point A is culvert critical to preventing hydrologic connectivity between the Rush River and Huelskamp Creek/Minnesota River to the south. Inset: a topographic cross-section across the south shore indicates that Clear Lake is contained by a 1m-high berm.
Points 4 and 13:
These points were selected because the divide follows a road and ditches are visible close to divide. The density of artificial drainage in the area arouses suspicion about the presence of a culvert under the road at these points. A culvert at either point 4 or 13 could be detrimental. A topographic cross-section across the road indicates that the divide here is steep, and 6m high, which makes a ditch unlikely. However, it may be good practice to field-check that there is not a culvert under the road in these locations.

Figure 15: Peterson and Swan Lakes at the south end of the Rush River watershed. Without clearly a clearly-defined relationship to Swan Lake, Peterson Lake could drain either north to the Rush River or south to Swan Lake (Point 10). Culverts and berms near point 10 would enforce drainage of Peterson Lake to the south. An impermeable berm at point 4 would strengthen the divide there.
Point 10:

Point ten was initially identified by a large discrepancy between the topographically-delineated watershed and DNR watershed. It appears that a road crosses a large wetland complex between Peterson and Swan Lakes at the south end of the Rush watershed. Topographically-delineated watershed divides indicate that separation depends on culverts below the road that allow Peterson Lake to drain south and an impervious boundary with the Rush to the north (Figure 16). While two culverts under the east-west road are evident on the DEM (Figure 15), a culvert also exists under the north-south road (near point A) which may allow connectivity with the Rush. At this time, the condition of levees and culverts is not clear, so it is not clear where water from Peterson Lake will flow. It may be prudent to reinforce or more clearly define the divide near point 10.

To the south of Peterson Lake, Swan lake intensively managed by DNR as a wildlife management area (Mahmoodi, 2001). The level of Swan Lake is managed by dam at its south end. If the lake level gets high enough, there does not appear to be anything stopping it from flowing north to Peterson Lake. Connectivity between Peterson Lake and the Rush River watershed could therefore connect Swan Lake to the Rush River. It might be safe to assume that the DNR has a clear understanding of hydrology in the management area, but a breach into Swan Lake seems possible and could be a problem for wildlife managers there.

Figure 16: The topographically-delineated stream network near point 10 suggests that discharge through the culvert on the right side of this image may be critical to maintaining watershed separation.
Point 16:

Present watershed boundaries at point 16 depend on culvert functionality. At this site, a ditch passes through 3 culverts as flows across a slope (Figure 17). For water to follow the ditch (and not the topography) the culverts must remain open. This site was identified based on the difference between the topographically-delineated watershed divide and the divides from the DNR.

Figure 17: DEM of point 16 and vicinity.
Point 20:

Point 20 was identified using the topographic position index layer. The TPI layer at this point shows a small, private ditch crossing the DNR divide and oriented towards a municipal ditch. High local relief is evident from the incised stream valley through which the municipal ditch flows, and sets the stage for a breach of the variety observed in the Des Moines headwaters. However, when a DEM of the area is studied, it is clear the divide here is an 8m high ridge and the ditch is superimposed on the ridge. It seems unlikely that the ditch could be deep enough to breach the divide or that water in the ditch could rise 8m and connect the two watersheds. This potential breach point illustrates the usefulness of topographic cross sections to help understand topography. However, this site should probably still be field-checked.

![Graph showing topographic cross section of Point 20]

Figure 18: A ditch appears to cross the watershed divide on the TPI layer. However, the DEM shows a 4m-high divide.
**Point 21:**

Like point 20, this potential breach point was also initially identified on the TPI layer. The TPI layer shows a straight, deeply-incised channel (Figure 19). Such a geometry suggests rapid stream incision, and because the channel is close to the divide, it aroused concern. Perhaps recent changes in the area precede hydrologic connectivity across the divide. However, when the larger-scale topography of the area is viewed, it is clear that the Minnesota River valley is the cause of steep slopes in the area (Figure 20). Tributaries of the Minnesota River are rapidly evolving over geologic timescales (Gran et al., 2009). Over human timescales, the landscape near this point may not be changing much at all. Incision by the ravines to the northeast and southwest of point 21 may shift the divide in the area over hundreds or thousands of years, but it is unlikely that recent changes drive the incision of this channel. This point is probably of low concern to land managers.

![Figure 19: Topographic position index in the vicinity of potential breach point 21.](image-url)
Points 20 and 21 illustrate the great power of the Topographic Position Index to highlight water-conveyance features in the landscape. However, these features do not always indicate inter-watershed hydrologic conductivity is present or even imminent. Ditches show up on the TPI layer so well because it highlights small topographic differences on the landscape. The tradeoff is that larger-scale landscape trends are more difficult to see. The larger topographic and geologic context of every potential breach point are important, but this is particularly true for points identified with the TPI layer.
**Point 5:**

This point was originally selected because the divide follows a large road. A cross-section suggests that this is a well-defined divide (Figure 21). It is also low in the watershed with clear stream valleys on either side. It is probably of little concern and unlikely to be the site of a culvert under the road. This point, along with points 4, 5, and 13, indicate that breaches in the Rush watershed are not necessarily likely where watershed divides follow roads. Note, however, that properly functioning road berms and culverts near divides are important for preventing inter-watershed hydrologic connectivity at most other potential breach points in the watershed (e.g., points 1, 12, 7, 10, and 16).

*Figure 21: Topography near potential breach point 5.*
Discussion

The breach sites this project identified in the Rush watershed look different than the sites on the Des Moines headwaters. The Des Moines headwaters have relatively high relief; points of inter-watershed connectivity there were identified in places where linear glacial topographic depressions cross watershed divides orthogonally. Potential connectivity between the Red and Minnesota Rivers also occurs in an outwash channel, but in a low-relief landscape. Tunnel valleys were identified in the Rush, but there appear to be other, more problematic potential breach sites in the low-relief watershed. Because of the historic hydrologic connectivity between prairie potholes, it seems more likely for breaches to happen at prairie potholes along the watershed divide.

In different glacial settings, artificial drainage may affect watershed connectivity differently. At potential breach sites in the Des Moines headwaters, artificial drainage infrastructure promoted connectivity. In the Rush, artificial drainage creates drainage where it wasn’t previously, so drainage in the Rush may help reduce watershed connectivity.

This study also identified breaches which may occur following failure of particular culverts or drainage infrastructure. A framework of breach types may be useful in identifying other potential breach sites in Minnesota (Table 1). As work on this problem progresses, it will be interesting to see if potential breach sites elsewhere in the state fall into the categories defined here.

<table>
<thead>
<tr>
<th>breach type</th>
<th>local relief</th>
<th>glacial setting</th>
<th>locations observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>linear glacial topographic</td>
<td>high or low</td>
<td>tunnel valley, outwash channel or nested moraines perpendicular to</td>
<td>Rush, DMH, Red-Minnesota</td>
</tr>
<tr>
<td>depression</td>
<td></td>
<td>nearly perpendicular to modern divides</td>
<td></td>
</tr>
<tr>
<td>unditched depression</td>
<td>low</td>
<td>ground moraine</td>
<td>Rush</td>
</tr>
<tr>
<td>critical drainage infrastructure</td>
<td>high or low</td>
<td>any</td>
<td>Rush, DMH</td>
</tr>
<tr>
<td>permanent connection</td>
<td>high or low</td>
<td>any</td>
<td>DMH</td>
</tr>
</tbody>
</table>

Note: DMH = Des Moines Headwaters

Fundamentally, methodology proposed by this project is meant to be quickly and easily accessible to analysts with a wide range of GIS skills, and therefore did not use hydrologic modelling. However, it was initially hoped that a simple topography-based model could be used to help objectively prioritize potential breach sites. The Floodplain Mapper Tool (Belmont, 2011) was investigated. This tool is designed for use on channels with geomorphic floodplains where it uses the slope of the floodplain to set the surface slope of the hypothetical floodwater. Upland prairie potholes drained by
artificial channels do not have a geomorphic floodplain. When the tool was used on pothole in the Rush, inundating water surfaces were based on the slope along the crest of ditch spoil piles or cross sections along pothole floors. Resulting water surfaces had unrealistically high slopes. In the prairie pothole landscape of the Rush, it might be more accurate to assume that the surface of the inundating water has no slope, and simply collects in closed basins until it overtops them. In this case, a comparison between the volume of closed depressions and the upstream catchment area would predict the amount of runoff required to overtop a closed basin. Such analysis is easy to perform in ArcGIS, but the hydrologic landscape of the Rush is so altered that it is difficult to find an unditched pothole. Furthermore, we might be justified in assuming that tile drainage in the Rush is common where potholes are not drained surficially (Shottler et al., 2013). Because drainage is common in the Rush, such a simple analysis is unlikely to reflect reality, and was not used in this study. The few sites where unditched potholes do exist close to the divide could be the sites of future in-depth field or modeling investigations. Here, they are considered potential breach points. Because it is very difficult to obtain records of subsurface drainage extent, this project does not explicitly address watershed breaches in subsurface drainage. However, because potential drain tile breach points were associated with outwash channels in the Des Moines, methods proposed here identify places where tile may be problematic.

A few other caveats about this project should be noted. This project does not address common carp, which have been widely distributed throughout Minnesota since the early twentieth century (Bajer and Sorensen, 2010). Unlike invasive carp, common carp prefer to live in still water, are benthic feeders, and are native to eastern Europe. But like invasive carp, common carp are migratory and cause ecological problems throughout watersheds (Bajer and Sorensen, 2010). Common carp are even believed to have migrated into fields through drain tile (Frohnauer, private communication). The ecological damage wrought by common carp, and their ability to migrate through tile lines may be a warning of invasive carp problems yet to come.

In spite of identifying potential breach sites in a number of different ways, this project did not develop methods to assess the probability that potential breach points identified might become actual breaches. This project focuses on carp’s ability to migrate into watersheds by swimming in surface waters, but carp can also enter watersheds by accidental release – such as by fishermen – or by intentional release. Furthermore, this project does not account for the economic or ecologic value of resources potentially lost after a watershed breach or the likelihood that a breach leads to an established population of invasive carp. Comprehensive environmental risk assessment is a big process with many requirements (Fishpro, 2004). This project only addresses a small component of the risk.
assessment process and should be used in conjunction with other analyses and in collaboration with
other scientific experts and resource managers.

Watershed breaches are a complicated hydrologic management problem. Difficult hydrologic
management problems are often addressed with hydrologic models (for example, flooding in the Red
River Valley; VanOffelen and May, 2013). Hydrologic modelling might be able to identify more potential
breach sites, or help prioritize work on potential breach sites by estimating the hydrologic conditions
under which breaches might occur.

Conclusions
This project suggests ways to leverage widely-available GIS resources to identify sites where
invasive carp might potentially breach watershed divides. Minnesota’s varied glacial landscape sets the
stage for a variety of different types of watershed breaches. In steep and low-relief parts of the state,
the DNR is working to mitigate potential breach sites – often enhanced by artificial drainage – on
watershed divides that cross linear glacial topographic depressions. Such sites should be identified as
potential breach sites in other watersheds. It is clear that modern hydrology is heavily influenced by
artificial drainage. Prior to modern agricultural drainage practices, surficial hydrology of prairie potholes
was much more interconnected (Winter and LaBaugh 2003). In contrast to watersheds with better-
declared glacial meltwater channels, it is likely that agricultural drainage more clearly defines modern
divides and reduces the occurrence of potential breach sites in low-relief landscapes such as the Rush.
The rich supply of GIS resources available in the state of Minnesota can also be used to identify drainage
infrastructure that is potentially critical to preventing watershed breaches. However, the methods
described here are not a “silver bullet” with which to identify all potential watershed breaches, and
should be used in conjunction with other breach identification and management efforts. Whatever the
method used to identify potential breach sites, the careful analyst would do well to keep glacial history
in mind.
GIS resource index

Aerial photos by county (digital orthoquads) from the Farm Service Administration/MN Geospatial information office: http://www.mngeo.state.mn.us/chouse/airphoto/fsa.html

DNR data deli: http://deli.dnr.state.mn.us/

Floodplain mapper tool from Patrick Belmont: http://www.nced.umn.edu/content/stream-restoration-toolbox

Hydrology toolbox, ESRI's help in use of:

Lake shapefile from the National Hydrology Dataset: http://nhd.usgs.gov/

Lidar data from the DNR: http://www.dnr.state.mn.us/maps/mntopo/index.html


Lidar training materials website from The University of Minnesota Water Resources Center: http://wrc.umn.edu/randpe/agandwq/tsp/lidar/LiDARTrainingMaterials/index.htm

Topographic Position Index:
An ArcGIS plug in that automates TPI creation (Majka et al., 2007): http://corridordesign.org
The DNR’s Sean Vaughn’s discussion of TPI: http://wrc.umn.edu/prod/groups/cfans/@pub/@cfans/@wrc/documents/asset/cfans_asset_383338.pdf
Further discussion of TIP and manual methods to create a TPI layer: http://gis4geomorphology.com/roughness-topographic-position/

Wetlands from the National Wetland Inventory (USFWS, 1980): http://www.fws.gov/wetlands/


Fishpro Consulting Engineers and Scientists (Fishpro), 2004. Feasibility study to limit the invasion of Asian Carp into the Upper Mississippi river basin. Prepared for the Minnesota Department of Natural Resources in cooperation with the Wisconsin Department of Natural Resources and the U.S. Fish and Wildlife Service (Region 3). Final Report, March 15, 2004, Springfield, Illinois. 253 pp.

Frohnauer, N. DNR Invasive Fish/River Habitat Coordinator. Private communication 10/9/2014.


