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Aquatic Ecosystem Health & Management

ISSN: 1463-4988 (Print) 1539-4077 (Online) Journal homepage: http://www.tandfonline.com/loi/uaem20

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To cite this article: John Stille, Namrata Shrestha, Ralph Toninger, Carissa MacKenzie, Andrew Ramesbottom & Joel Smith (2018) Integrated restoration prioritization–A multi-discipline approach in the Greater Toronto Area, Aquatic Ecosystem Health & Management, 21:3, 352-361, DOI: 10.1080/14634988.2018.1507408

To link to this article: https://doi.org/10.1080/14634988.2018.1507408

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Integrated restoration prioritization–A multi-discipline approach in the Greater Toronto Area

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Ecosystem restoration planning requires an integrated approach considering many components of the natural system when prioritizing where and what to restore. Toronto and Region Conservation Authority and partners have developed a multi-discipline and multi-benefit approach to restoration planning that facilitates effective restoration works, which contribute to realizing regional watershed objectives pertaining to natural system functions. Through various long term monitoring and modeling initiatives, Toronto and Region Conservation Authority has amassed a wealth of knowledge on terrestrial biodiversity, aquatic ecosystems, hydrology, and headwater conditions. The aim of Integrated Restoration Prioritization is to identify impairments and threats to ecosystem function as a means to improve the delivery of ecological goods and services. Consolidating data and comparing discrete areas based on different parameters and thresholds can help direct decision making for future restoration initiatives. The first iteration of the Integrated Restoration Prioritization analyzed existing datasets, identified gaps, and made recommendations for future monitoring. This approach will assist with delisting Beneficial Use Impairments #14 Loss of Fish and Wildlife Habitat and #3 Degradation of Fish and Wildlife Populations within the Toronto Remedial Action Plan area. Further, the Integrated Restoration Prioritization will assist in implementing the recommendations made in watershed planning documents pertaining to fisheries and natural heritage management. Specifically, the Integrated Restoration Prioritization will identify where impairments to ecological function are located, ensure habitats and corridor linkages are protected or restored, and prioritize local and upstream catchments that could contribute most to improving the natural system if restored.

Keywords: natural cover, strategic, tool, targets, impairment, restore, implementation

Introduction

Land use changes associated with urbanization have substantial impact on the structure and function of natural systems (Grimm et al., 2008; Forman, 2008). This is mainly because urban land uses change natural land cover more drastically than any other land use and are more persistent on the landscape (Marzluff and Ewing, 2001; Theobald et al., 2011; Hanna and Webber, 2010; McKinney, 2006). Among the various impacts, urbanization result in loss and fragmentation of natural cover, which in turn has several direct and indirect impacts on ecological functions of the landscape (Grimm et al., 2008). This includes loss and isolation of biodiversity and

Aquatic Ecosystem Health & Management, 21(3):352–361, 2018. Copyright © 2018 AEHMS. ISSN: 1463-4988 print / 1539-4077 online
DOI: 10.1080/14634988.2018.1507408

habitat, extirpation of sensitive species, altered hydrology, nutrient cycling, and changes in water quality and quantity (Fahrig, 2003; Marzluff and Ewing, 2001; McKinney, 2006).

The Secretariat of the Convention on Biological Diversity (2012) has estimated that by 2050 the world population living in urban areas will nearly double. It further estimates that more than 60% of these urban areas are not yet built and are expected to happen in small and medium sized cities such as Toronto. As these future urban areas are developed more natural cover will be lost and fragmented. This will continue to have detrimental impacts on ecological functions that, ultimately, will compromise the ecosystem services required for planetary and human well-being (Grimm et al., 2008; McPhearson et al., 2016). A strategic framework for ecological restoration that focusses on mitigating human induced impairments to ecological function and building on and connecting existing natural cover will be critical to influencing future land management decisions. Ecological restoration aims to assist in repairing, rehabilitating, and recovering ecosystems that have been degraded, damaged or destroyed. The goal is to re-establish the desired characteristics of the ecosystem that were important for ecological function before the degradation, such as natural cover (Benayas et al., 2009). More recently ecological restoration has gained interest in specifically targeting increases in services that ecosystem structure and functions provide to benefit human well-being (Benayas et al., 2009). This expanded focus has made restoration of natural features and processes, especially in urban areas, all the more important as the rationale for restoration is emphasizing on a wider spectrum of benefits beyond providing habitat for species. While ecological restoration as a process identifies the best ways to restore at a site level, it is also critical to understand where to conserve and restore to achieve effective overall natural system outcomes (Margule and Pressey, 2000). There are multiple approaches in systematic conservation planning that have tried to address this spatial aspect of conservation and restoration planning (Sarkar et al., 2006). The added challenges in restoration planning include addressing ongoing disturbances, choosing between creating new habitat verses restoring existing degraded features, improving areas of severe degradation verses areas that are less degraded, and determining outcomes that measure success.

In this article we present a multi-objective, scalable and spatially explicit framework to prioritize ecological restoration initiatives in the nine watersheds within the Greater Toronto Area (GTA) as a case study that could be applied at a broader scale. The Integrated Restoration Prioritization (IRP) framework is to be used as a decision making tool to direct resources and funds to restoration efforts that could achieve the most collective benefit to the natural system. Similar strategies have been applied to other areas which generally focus on habitat availability, environmental stressors, connectivity, restoration costs and land-use threats (Tambosi et al., 2014, Crouzeilles et al., 2015, Evans et al., 2006). These strategies are typically based on conceptual models that are applied spatially as GIS overlays. This framework builds on these studies by overlaying long-term environmental monitoring data used to report on overall watershed health onto conceptual landscape models to identify where discrete areas of impairment are located within high valued potential natural heritage areas. IRP has a strong focus on natural cover and hydrology as the two main drivers for natural system function.

IRP reflects multi-discipline watershed management objectives of enhancing terrestrial and aquatic habitat, improving surface and ground water, and maintaining headwater streams. More specifically, the restoration initiatives identified through the IRP can be implemented to support the Toronto and Region Remedial Action Plan (RAP) Recommended Action 21: "Protect and Restore Fish and Wildlife Habitat," and RAP Goal 2b: "Rehabilitation of Fish and Wildlife Habitat." This approach will assist with delisting Beneficial Use Impairment (BUI) #14 Loss of Fish and Wildlife Habitat and BUI #3 Degradation of Fish and Wildlife Populations within the Toronto AOC.

The fundamental principle of the IRP is to prioritize locations where restoration can achieve the greatest benefit through reversal or mitigation of existing impairments in areas that will have the most benefit to natural system function. This is based on four fundamental restoration objectives: (1) increasing natural cover; (2) restoring altered hydrology and aquatic impairments; (3)

maximizing size, shape and connectivity of natural features; and (4) restoring landform alterations to promote self-sustaining natural communities.

Methodology

Study area

The nine watersheds of the GTA that lie within Toronto and Region Conservation (TRCA) jurisdiction is the study area for the IRP framework presented in this article. Six of the nine watersheds are located within the Toronto and Region AOC (excluding Duffins, Carruthers and Petticoat watersheds). These nine watersheds are some of the most heavily urbanized watersheds in Canada. Natural cover within these watersheds ranges from 10 to 40% indicating that these watersheds are generally below recommended natural cover of 30 to 50% (Pressey et al., 2003; Nature Conservancy of Canada, 2004; Noss et al., 2012). Recognizing that the pace of urbanization in the GTA will continue to threaten the remaining natural cover and biodiversity, TRCA developed the Terrestrial Natural Heritage System Strategy (TNHSS) (TRCA, 2007a,2007b). Based on systems thinking and landscape ecology principles the TNHSS delineated a target Terrestrial Natural Heritage System (TNHS) comprising of both existing natural cover areas and potential areas where natural cover could be restored to increase the quantity and quality of natural cover and biodiversity within the GTA. TRCA's Regional Watershed Monitoring Program (RWMP) has been assessing aquatic and terrestrial conditions in TRCA's jurisdiction for decades informing on the current ecological health of the watersheds as well as highlighting trends over time (TRCA, 2017). Aquatic monitoring utilizes the Ontario Stream Assessment Protocol (OSAP), which is a standardized set of provincially and federally recognized methods for determining stream health. Using data generated from these two programs, the IRP framework outlined in this paper provides a systematic approach for restoration planning across the urban to rural gradient.

Data

Nine data sets were selected for use within the IRP framework based on an internal peer review of their relevance to restoration objectives, spatial coverage, and accuracy. These data were collected and compiled from multiple sources within TRCA including field and modelled data, as well as direct orthophoto interpretation. Each data set was organized into four ecological or natural systems criteria to reflect the different objectives within the IRP framework (Table 1).

Delineating catchments as the spatial unit of assessment

For TRCA's entire jurisdiction, discrete catchments (the spatial unit of assessment for IRP) were delineated using surficial drainage patterns and ArcHydro modelling. ArcHydro is an Esri ArcGIS application where drainage lines and catchment boundaries are derived from a Digital Elevation Model (DEM). The DEM was generated from real elevation data and has an accuracy of approximately 0.25 metres. This execution of the IRP analysis used 30 hectare (on average) catchment boundaries. The data used for analysis was applied to each catchment and thresholds were used to generate scoring for comparison and prioritization.

Natural systems criteria and scoring for prioritization

Each of the four natural system criteria; namely existing natural cover, altered hydrology, aquatic condition, and terrestrial natural heritage potential were derived based on a number of individual data layers as listed in Table 1. Threshold criteria were assigned to each dataset to target a specific impairment in need of restoration. A score was applied to each dataset based on how it satisfied that threshold criteria. Each of these individual data layers was summarized into categorical maps with the catchment resolution to reflect how the scores were applied. The catchment maps were used as overlays and the individual scores were summed to determine a total score that reflected the restoration priority for each catchment within the study area as described in the following sections.

Table 1. Summary of the four major criteria for Integrated Restoration Prioritization.

Metric	Catchment Limit Threshold	Restoration Rationale
Natural Cover Criteria		
Percent Riparian Cover	Below watershed percent average =1	Areas in need of more cover
Percent Wetland Cover	Below watershed percent average =1	Areas in need of more cover
Percent Forest and Successional Cover	Below watershed percent average =1	Areas in need of more cover
Altered Hydrology Criteria		
Altered Hydrology	Based on the Severity Assessment Criteria (Low =0; Medium =1; High =2)	Areas where impairments and threats to hydrologic function are likely and are in need of restoration/remediation
Aquatic Condition Criteria		
In-Stream Temperature	Stable and moderate =0; Unstable and extreme =1	Upstream areas that are in need of mitigation to reduce in-stream heating
Priority and Known Barriers identified through Fish Management Plans	Occurrence =1	Areas where facilitating fish movement is needed
Water Quality (FBI and IBI)	FBI: fairly poor, poor, very poor =1; Good Fair =0 Or IBI: fair, poor, no fish =1; Good Very, Good =0	Upstream areas that are in need of mitigation to improve water quality
Terrestrial Natural Heritage Potential Criteria		
Ecological Value Surface score	Below average percent natural cover and above average ecological value surface score =1	Areas to increase natural cover that are adjacent to areas of significant existing cover
Terrestrial Habitat Connectivity Within the Target TNHS	Below average percent natural cover and above average terrestrial habitat connectivity score =1	Areas of low natural cover that can contribute most to connecting areas of good natural cover
Wetland Connectivity	Below average percent wetland cover and above average wetland connectivity score =1	Areas of low wetland cover that can contribute most to connect good wetland cover

Existing natural cover

The existing natural cover category is represented by the three metrics; namely percent area riparian, wetland, and forest cover within each catchment. Natural cover data was derived from a standardized interpretation of orthophotography where riparian, wetland and forest cover have been spatially delineated. The percent area of natural cover for three metrics was calculated within each catchment and compared against their respective watershed average percentages. Catchments that had *below* average percent natural cover were given a score of 1 inferring impairment and that the catchment was in need of more of that particular cover type. When all three metrics were aggregated the range of potential score was 1 to 3, indicating the catchments that are in low, medium, high need of natural cover respectively (Figure 2a).

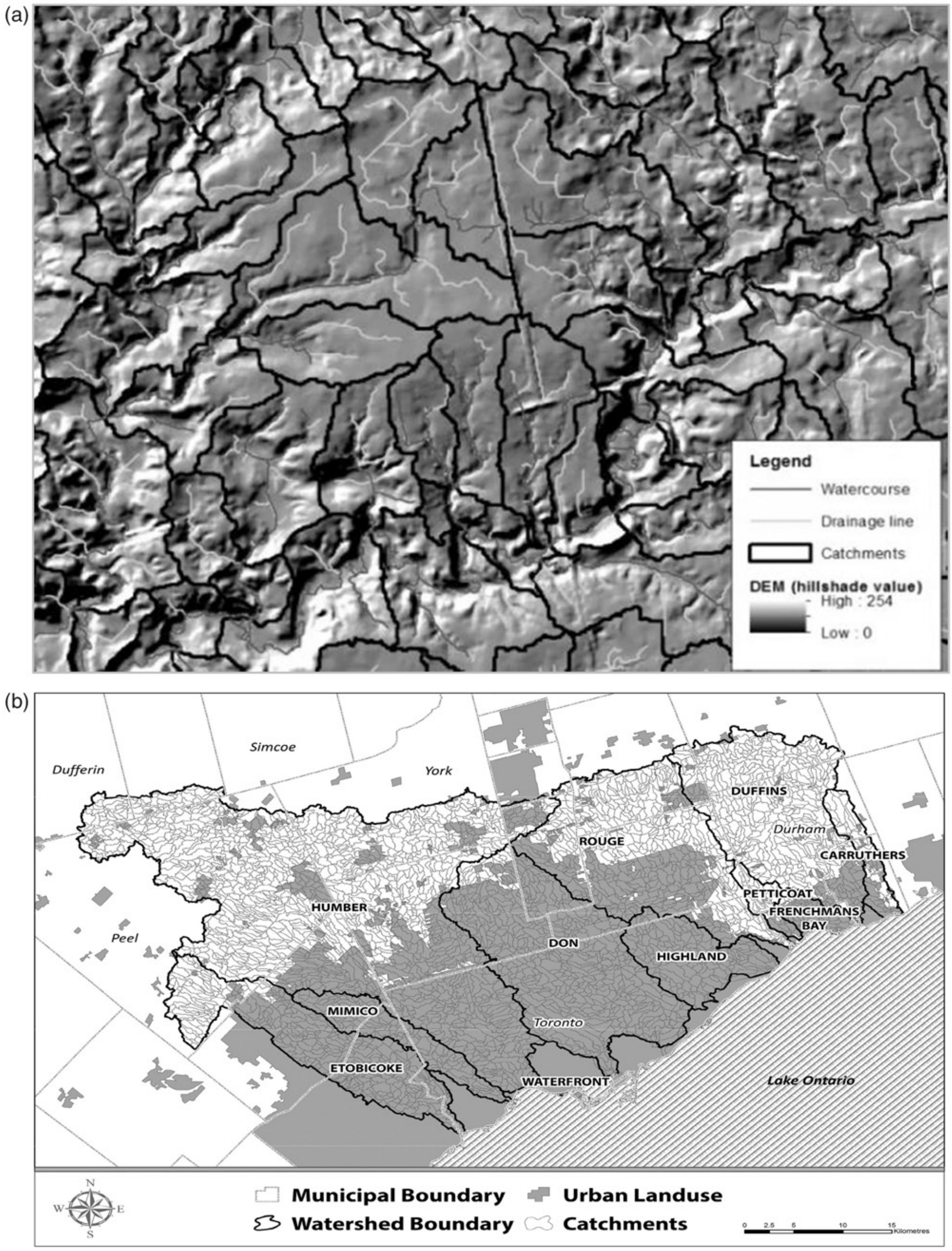

Figure 1. (a) Digital Elevation Model (DEM) and (b) Arc Hydro catchments modeled from 30 ha drainage lines across urban, urbanizing, and rural parts of TRCA's nine watersheds.

Altered hydrology

A standard method of orthophoto interpretation was developed specifically for this analysis to determine the extent of anthropogenic stressors across TRCA jurisdiction. Four metrics were used to determine the severity of altered hydrology; namely percent coverage of straightened reaches, presence of on-line ponds, presence of tile drainage, and percent of urban cover. The catchments were ranked as low, medium, and high based on how many criteria were satisfied

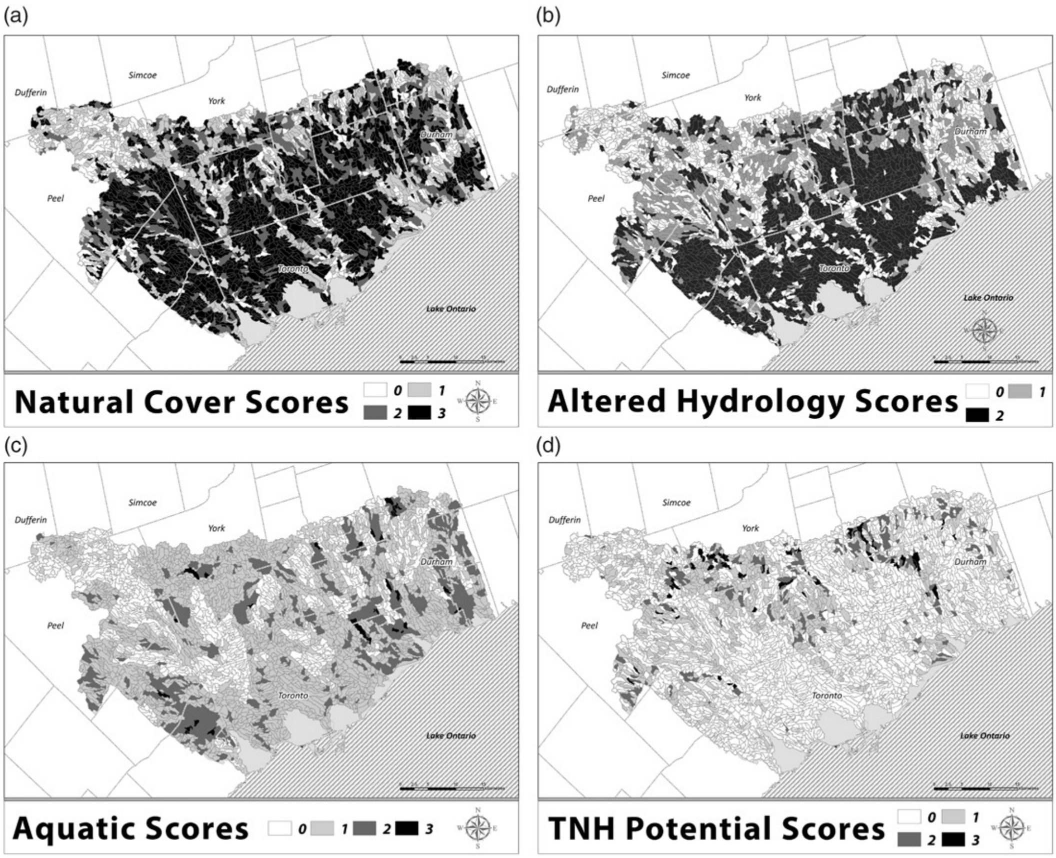

Figure 2. TRCA-wide natural system criteria scores: (a) Natural Cover Scores; (b) Altered Hydrology Scores; (c) Aquatic Scores; (d) Terrestrial Natural Heritage Potential Scores.

and this was then translated into numeric scores of 0, 1 or 2 respectively with 2 denoting higher hydrologic alteration (Figure 2b). To minimize subjectivity during assessment, two separate assessors used these criteria to score each catchment individually. Where the scores were different between the two assessors, a third assessor was used to determine a final score for those catchments.

Aquatic condition

Three metrics were chosen to indicate aquatic conditions; namely temperature, in-stream barriers, and water quality indices. Pre-existing thermal data collected at 179 stations from 2005–2008 via TRCA's RWMP and were evaluated to determine whether in-stream water temperatures were stable and moderate or unstable and extreme to assign a score of 0 or 1, respectively (Wehrly et al., 1999). These scores were applied to the catchments with a RWMP monitoring station and all relevant upstream catchments. In-stream barriers were assessed based on the occurrence of known dams, weirs and on-line ponds to assign a score of 1 if the barriers were present. Water quality data was collected at 303 sites from 2002 to 2012 via TRCA's RWMP and was evaluated using field data indices, benthic invertebrate Family Biotic Index (FBI) and fish Index of Biotic Integrity (IBI) as proxies for water quality (Dauer et al., 2000; Rosenberg and Resh, 1993). TRCA's RWMP recognizes benthic communities as a stronger and more rapidly detectable indication of water quality (Dauer et al., 2000; Rosenberg and Resh, 1993); however, there were a few monitoring stations where only fish sampling data were available. At these sites, the FMP IBI data were used to maintain a relatively even distribution and density of data across the study area. The catchments with an FBI rank of fairly poor to very poor and IBI rank of fair, poor, and no fish were assigned the score of 1 indicating the presence of an aquatic impairment (Figure 2c) which was applied to all relevant upstream catchments.

Terrestrial natural heritage potential

Three metrics were used in conjunction with the natural cover layer to reflect the potential terrestrial natural heritage criteria; namely ecological value surface, terrestrial habitat connectivity, and wetland connectivity. Ecological Value Surface (ESV) raster and scoring method was developed for existing and potential cover areas across the study area (TRCA, 2007b). The ESV used 18 peer reviewed ecological and land use criteria to reflect specific landscape conditions and applied them to 10 m x 10 m pixels with scoring to rank its existing or potential ecological value to the natural system. Criterion and scoring for the ESV included data such as: distance from urban areas; proximity to natural features; Interior forest; proximity to other cover types; ownership; areas under special regulation or protection designation (e.g. Provincially Significant Wetlands); or any land-use planning policy initiatives that provided natural area protection (e.g. Ontario Greenbelt Plan). Any catchments that had higher than average ecological value score but also had lower than average existing natural cover were assigned a score of 1 indicating a priority for restoration. TRCA has also developed a predictive terrestrial habitat connectivity layer as well as a wetland connectivity layer using a circuit-theoretic approach (McRae et al., 2008), which provides relative contribution of each location within the entire jurisdiction to maintaining the overall connectivity of existing habitat patches. For terrestrial habitat connectivity, high quality habitat mosaic patches (TRCA, 2007b), which included all forest, wetlands, meadows, and successional areas, were used as the "core habitat" to connect in the Circuitscape modeling. This approach goes beyond species or guild specific focus, instead ensuring that all habitat patches that have been deemed important for regional biodiversity in TRCA's TNHS Strategy (2007a,2007b) are well connected for present as well as for future conditions. The Circuitscape model (McRae et al., 2008) was run to identify connectivity at the regional scale at 10 metre resolution and later scaled up to the catchment scale for IRP purposes.

Wetland connectivity analyzed the connectedness of forest and wetland patches using spring peeper habitat requirements as an assumed surrogate. Spring peepers are a local species of concern for TRCA and appropriately represent the semi-terrestrial amphibians in the jurisdiction that require migration to wetlands (swamps, marshes, ponds) for breeding in spring and to upland forested habitat for the rest of the year to forage and hibernate. Based on the habitat requirement analysis for spring peeper using TRCA long term monitoring plot data, literature review, and expert's knowledge, all wetlands with more than or equal to 30% forest cover within 300m of the wetland boundary were delineated as the "core habitat" patches for which landscape connectivity is desired. In addition, all other wetlands larger than 2 ha were also included in the "core habitat" map with an assumption that larger mapped wetlands have greater opportunity to contain a mosaic of wet and dry patches within it to support all wildlife represented by the focal species. The Circuitscape model (McRae et al., 2008) was run to identify connectivity at the regional scale at 10m resolution and later scaled up to the catchment scale for IRP purposes.

Any catchments that had above average terrestrial and wetland connectivity scores but also had below average natural and wetland cover respectively were assigned a score of 1 each indicating restoration priority to improve spatial cohesion among the patches and build resilient habitat networks (Opdam et al., 2003, 2006). When all three metrics were aggregated, the range of potential score was 1 to 3 with higher scores denoting higher priority (Figure 2d).

Integrating multiple criteria into Integrated Restoration Prioritization Framework

The aggregated scores for all metrics representing the four natural system criteria (Figure 2) were overlaid in GIS to develop an IRP layer (Figure 3) that was used to determine the overall

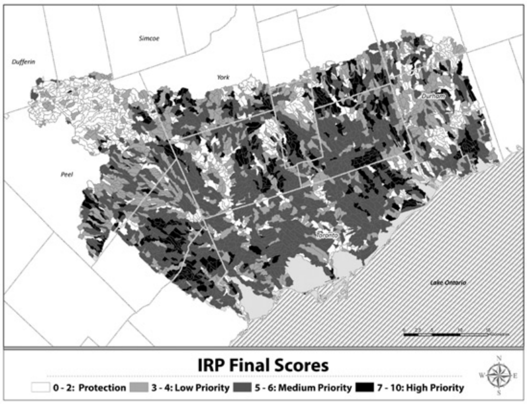

Figure 3. TRCA-wide final IRP scores and priority ranks.

restoration priorities across the nine watersheds of the TRCA jurisdiction. The overall score in the final IRP layer ranged from 0 to 11 accounting for all metrics used.

Results

Figure 3 illustrates the spatial distribution of the IRP ranks across all catchments of TRCA's nine watersheds. Most of the catchments (39%) in TRCA's jurisdiction are of medium priority, followed by low priority (27%), and then by high priority (12%) for restoration. Almost one fourth of these high priority catchments are located within the Highland watershed followed closely by Etobicoke, Mimico, and the Rouge watersheds at 22%, 22% and 17% of the high quality catchments respectively.

In terms of the land use gradient, urban areas contain a substantial number of medium to high priority catchments (67%). As expected, this is primarily driven by low natural cover, high altered hydrology and low water quality. Altered hydrology and low natural cover is prevalent across urban areas except where catchments contain wide valley and stream corridors with limited development and higher amount of vegetation. In rural regions the areas with significant altered hydrology are more sporadic and mostly reflect the isolated areas of intensive agriculture that are affecting headwater reaches (e.g. straightened or ditched channels, tile drains and on-line ponds). In terms of the aquatic criteria, the higher scoring areas are along the outer boundaries of development where land use transitions from urban to rural. These are mostly in upper Duffins and Rouge watersheds where higher density rural dwellings and intensive agriculture exist. Lastly, high priority areas for terrestrial natural heritage potential are primarily along the southern boundary of the Oak Ridges Moraine where development pressures are moving into large expanses of greenspace and agricultural lands. These are the areas that have mostly low natural cover with high priority for habitat connectivity needs.

Much of the rural portions of the study area, such as northern section of Humber and Duffins watersheds, have a final IRP score of 0-2, mainly due to the low overall impairment levels and higher value natural areas. These catchments are highlighted as "protection" areas requiring conservation efforts to support these natural cover strongholds emphasizing that they should receive restoration efforts to correct more acute impairments that might have significant local impacts (e.g. large on-line ponds in cold water protection reaches).

A rudimentary orthophotogrphy assessment of the results was performed to determine what common features pertain to low, medium, high and protection catchments. Figure 4 (available online in the supplementary files) outlines some general themes pertaining to each catchment priority type. Further analysis is needed to determine consistency over the entire jurisdiction within each catchment.

Discussion

The IRP framework is designed to be systematic, flexible and repeatable where new or updated data obtained through scientific studies can be incorporated into restoration prioritization. IRP incorporates a wide variety of restoration considerations into one platform to create a decision support tool in the form of user-friendly GIS mapping. Both the method and the results have already facilitated strategic restoration decisions within TRCA in terms of where to restore and what to restore, especially when there are competing objectives and multiple opportunities within a constrained budget.

The final outputs detail priority categories as well as a sum total IRP score. Beyond this, the results can be further refined based on individual metrics to achieve a specific goal or objective.

For example, if there is an interest in identifying areas to increase riparian cover for thermal mitigation, queries can be performed on the riparian results (i.e. catchments with below average riparian cover) and the temperature results (i.e. catchments with extreme or unstable temperatures) to highlight catchments that would best contribute to that objective if restored.

The IRP framework emphasizes that proper interpretation of the data (i.e. understanding what metrics within the analysis are driving priority; what are some of the data gaps; and local site level knowledge) is critical to developing an accurate understanding of ecological function and restoration priorities. For example regarding the aquatic data used, there was an assumption that all catchments upstream of a specific monitoring station influence the data results acquired from the immediate downstream monitoring station. Increasing the density of monitoring stations could improve validity and understanding of the relationship between upstream conditions and downstream impacts. Further, data used for this iteration of the IRP varied between watersheds depending on the temporal and spatial parameters. This understanding of gaps and inconsistencies in the data will help to guide future directions in data collection in order to increase consistency, distribution and accuracy of new datasets. The IRP analysis will be updated on a regular basis to ensure that the most current and appropriate data is incorporated as they become available.

Although the results demonstrate the differences between urban and rural landscapes, all data were treated similarly across the urban-rural gradient in how they were measured against their predetermined limits. Further, restoration costs were not considered in this analysis, primarily due to its variability especially between urban and rural landscapes. Continued analysis is needed to apply land use context based information that recognizes the differences between urban and rural influences as restoration approaches can differ between land-use types.

Conclusions

IRP is a decision support tool than can be used for a variety of ecosystem restoration and land management initiatives. The intent is to facilitate strategic planning regarding restoration that will have the greatest benefit to ecosystem health. The metrics used for the IRP analysis differs from other prioritization frameworks in that it utilizes a wealth of long-term environmental monitoring data collected regionally to make determinations on the health of watersheds within the Greater Toronto Area. The focus is on field verified metrics that highlight natural system impairments that active restoration can mitigate. As such, directing a critical mass of restoration efforts to priority areas could demonstrate a measured impact to ecosystem health which would be reflected in long-term monitoring and trends analysis. Restoration activities can be selected to directly address multiple watershed health benefits including, but not limited to, improved habitat availability, natural cover, base flow conditions, water quality, erosion control, and sedimentation abatement.

Implementing restoration projects within high priority catchments can help to address watershed scale fisheries management and watershed planning objectives which could contribute to delisting the Toronto and Region AOC. The IRP could also be used as a land-use planning tool to identify priority areas to preserve for restoration and protection through land acquisition or conservation easements. Further, IRP could be used to determine the most appropriate offset areas to compensate for unavoidable natural feature losses due to development pressures.

The IRP framework described in this document outlines the first iteration of IRP analysis. Future iterations will involve a continuous process of coordinating with interested stakeholders, updating data and adding supplementary data layers as they become relevant to prioritizing for restoration objectives.

Funding

The development of the IRP framework was funded by the Great Lakes Sustainability Fund (managed by Environment and Climate Change Canada), Region of Peel, York Region, City of Toronto, Durham Region and the Salamander Foundation.

Supplemental material

Supplemental data for this article can be accessed on the publisher's website.

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