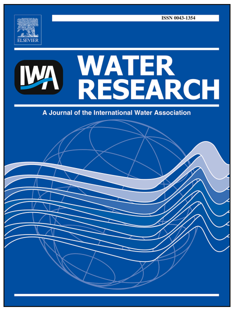

Replacing natural wetlands with stormwater management facilities: biophysical and perceived social values

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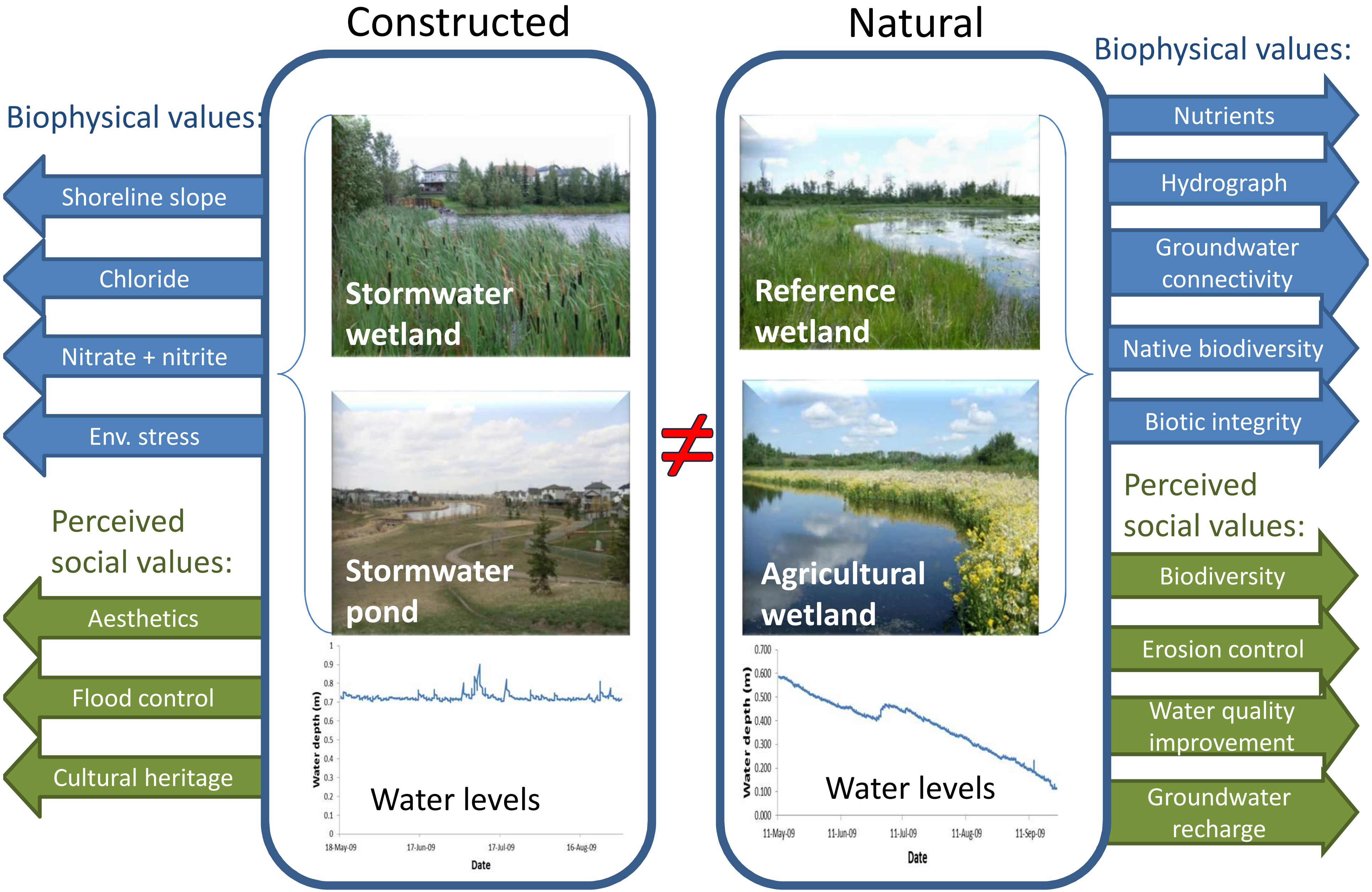
HIGHLIGHTS – Replacing natural wetlands with stormwater management facilities: biophysical and perceived social values.

- Stormwater ponds and wetlands are poor mimics of natural wetlands
- We observed differences in biodiversity, biotic integrity, hydrology and chemistry
- Stormwater wetlands were not substantive improvements over stormwater ponds
- Important drivers of wetland condition are poorly recognized by the public



Constructected

Constructed ≠ Natural

Biophysical values:
- Shoreline slope
- Chloride
- Nitrate + nitrite
- Env. stress

Perceived social values:
- Aesthetics
- Flood control
- Cultural heritage

Stormwater wetland

Stormwater pond

Water levels

Natural

Reference wetland

Agricultural wetland

Water levels

Biophysical values:
- Nutrients
- Hydrograph
- Groundwater connectivity
- Native biodiversity
- Biotic integrity

Perceived social values:
- Biodiversity
- Erosion control
- Water quality improvement
- Groundwater recharge

Title: Replacing natural wetlands with stormwater management facilities: biophysical and perceived social values

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ABSTRACT

Urban expansion replaces wetlands of natural origin with artificial stormwater management facilities. The literature suggests that efforts to mimic natural wetlands in the design of stormwater facilities can expand the provision of ecosystem services. Policy developments seek to capitalize on these improvements, encouraging developers to build stormwater wetlands in place of stormwater ponds; however, few have compared the biophysical values and social perceptions of these created wetlands to those of the natural wetlands they are replacing. We compared four types of wetlands: natural references sites, natural wetlands impacted by agriculture, created stormwater wetlands, and created stormwater ponds. We anticipated that they would exhibit a gradient in biodiversity, ecological integrity, chemical and hydrologic stress. We further anticipated that perceived values would mirror measured biophysical values. We found higher biophysical values associated with wetlands of natural origin (both reference and agriculturally impacted). The biophysical values of stormwater wetlands and stormwater ponds were lower and indistinguishable from one another. The perceived wetland values assessed by the public differed from the observed biophysical values. This has important policy implications, as the public are not likely to perceive the loss of values associated with the replacement of natural wetlands with created stormwater management facilities. We conclude that 1) agriculturally impacted wetlands provide biophysical values equivalent to those of natural wetlands, meaning that land use alone is not a great predictor of wetland value; 2) stormwater wetlands are not a substantive improvement over stormwater ponds, relative to wetlands of natural origin; 3) stormwater wetlands are poor mimics of natural wetlands, likely due to fundamental distinctions in terms of basin morphology, temporal variation in hydrology, ground water connectivity, and landscape position; 4) these drivers are relatively fixed, thus, once constructed, it may not be possible to modify them to improve provision of biophysical values; 5) these fixed drivers are not well perceived by the public and thus public perception may not capture the true value of natural wetlands, including those impacted by agriculture.

KEYWORDS: Agriculture, constructed wetlands, ecosystem services, wet ponds, wetland health, wetland services.

1.0 INTRODUCTION

Population growth and urban sprawl are on a continuing course of conflict with urban and suburban wetlands. Seventy percent of the world's population is expected to live in urban areas by 2050 (UN-HABITAT, 2008); however, in Canada this is already the case (StatsCan, 2012). The expansion of cities in response to growing urban populations is exacerbated by a global trend of suburbanization and sprawl whereby the surface area of cities grows more quickly than their populations (UN-HABITAT, 2008). The City of Edmonton (Alberta, Canada) is the second fastest growing metropolitan area in Canada: its population grew 12.1% between 2006 and 2011 (StatsCan, 2012) and 93% of Edmonton's growth during that same period was in suburban areas. Urban sprawl contributes to negative social (Clement, 2010) and human health effects (Ewing et al., 2003), as well as environmental degradation (Johnson, 2001). This includes increased carbon emissions (Seto et al., 2010), habitat degradation (Herrera-Montes and Aide, 2011) and water balance and quality issues (Brabec et al., 2002, Haase, 2009).

A concurrent increase in impervious surfaces and loss of natural wetland habitats associated with conversion from agricultural to suburban lands necessitates stormwater control measures (Bodnaruk et al., 2012). Wetlands are effectively replaced by constructed living spaces and excavated water holding facilities for runoff capture. For example, Edmonton estimates that 80% of wetlands have been lost from within its corporate boundary as a result of urban and suburban expansion (ONA, 2008).

Since the 1980s, the City of Edmonton has adopted a retention and channelization approach to stormwater management, using two types of stormwater management facilities linked to underground conduits to control flooding following heavy rainfall: stormwater ponds and naturalized stormwater wetlands (i.e., constructed wetlands). These stormwater management facilities currently process stormwater from 8,800 ha or 26% of Edmonton's urban footprint (Edmonton, 2010). Stormwater ponds and wetlands are almost exclusively a feature of suburban developments as municipalities have tasked developers with capturing first pulse rainfall runoff in the last 30 years. These runoff-capture facilities have also been re-cast as an aesthetic amenity for suburban dwellers, with terms like "lake-front property" and "homes with close proximity to park areas."

Stormwater ponds are more common than stormwater wetlands and typically consist of large open water areas with steep-sided slopes and minimal wetland vegetation, occasionally with bank stabilization of cobbles, brick or rip-rap and often surrounded by park-like landscaping. During the last decade, developers have been encouraged to build stormwater wetlands (Bodnaruk et al., 2012), which are designed to resemble natural wetlands with more gently sloping shorelines, increased emergent vegetation, and less open water area (see summary in Table S1).

The province of Alberta released a new wetland policy in September 2013, which is representative of the move towards value-based management of wetland resources currently taking place in many jurisdictions as the importance of ecosystem services is recognized (e.g., Eigenbrod et al., 2011, Marlow et al., 2013). This policy gives partial compensation credit for destroyed or altered wetlands to developers who build stormwater wetlands in place of stormwater ponds (GoA, 2013). The justification provided for this credit is the presumed provision of ecosystem services. Moore and Hunt (2012), for example, demonstrated that stormwater wetlands provide increased carbon sequestration and plant diversity relative to stormwater ponds.

However, these stormwater wetlands and ponds are replacing natural wetlands in peri-urban lands (e.g., Fig. S1), begging a comparison of stormwater management facilities and natural wetlands, not just a comparison between stormwater wetlands and stormwater ponds. We compared both stormwater ponds and stormwater wetlands to naturally occurring wetlands in agricultural and protected reference areas. Based on previous studies (e.g., Moore and Hunt, 2012, Wilson et al., 2013), we hypothesized that these categories would exhibit increasing "biophysical value" in the form of increased biodiversity, ecological integrity, and reduced environmental stress in the following order: created stormwater ponds, created stormwater wetlands, agriculturally impacted wetlands of natural origin, relatively undisturbed wetlands of natural origin. We name these wetland attributes values in recognition of their benefit to humans (Novitzki et al., 1996).

In any assessment of stormwater management facilities as compensation for natural wetlands, their value to the public cannot be simply confined to biophysical contributions because cultural, economic, aesthetic and security features of landscape types are also considered in policy formulation. Furthermore, while the public's awareness of ecosystem goods and services is broadened through more frequent discussion in schools, the media, policy debates and neighbourhood politics, most of the public likely lacks a critical level of basic knowledge about wetland ecosystem goods and services (Lewan and Soderqvist, 2002, Manuel, 2003) and the differences between natural and created wetlands.

There are substantive differences between natural and created wetlands. For example, stormwater management facilities are surface-water fed systems required to be totally isolated from groundwater by liners. In contrast, most natural wetlands in our study region are highly variable headwater wetlands with some degree of groundwater connection.   Run-off is minimal because soil storage capacities and potential evapotranspiration rates are usually high (Hogg, 1994), but many serve as either recharge or discharge sites for groundwater (Holden, 1993). Whereas stormwater management facilities are typically weir-controlled and possibly over-stabilized leading to altered vegetation (Wilcox et al., 1985), natural wetlands experience dramatic inter-annual differences in drying and wetting and open water storage, providing a myriad of niches. Do these fundamental differences affect ecosystem values in created wetlands?

Our objectives are twofold. First, we compare the biophysical values of natural wetlands to those associated with stormwater ponds and stormwater wetlands. Second, we compare resident perceptions of ecological services of natural wetlands and stormwater ponds with their biophysical values. The second objective is complementary to the first because it allows us to compare scientific assessments with social perceptions of ecosystem services. Recent evaluative work on Alberta's wetland policy has addressed the weak role of science in informing how biophysical values of wetlands are integrated into wetland permitting and compensation decisions (Clare et al., 2011, Clare and Creed, 2014), and stormwater ponds are increasingly replacing natural wetlands in peri-urban areas. This paper seeks to both inform readers about the biophysical values of stormwater ponds compared to natural wetlands and to determine the current resident understanding of the ecological services of these different systems. In particular, we are concerned with biodiversity, biological integrity, morphologic and hydrologic properties, and water and sediment quality as biophysical values. We also sought to fill a gap in the social science and interdisciplinary literature on the documented level of public understanding and appreciation of wetlands in terms of aesthetic, cultural heritage and existence values, as well as more pragmatic ecosystem services like flood protection, groundwater recharge and erosion control.

2.0 METHODS

2.1 Study region

Sampling was carried out in semi-permanent and permanent shallow open water marshes near the City of Edmonton, mainly within the Beaverhills sub-watershed of the North Saskatchewan River (Fig. 1), located at the northern margin of the prairies in the Aspen Parkland Ecoregion, Alberta, Canada. The topography of the area is flat to low morainal swales and surficial soils may include coarse outwash kame moraine, intermediate-textured moraine, fine-textured glaciolacustrine deposits, and dune field materials (Allan and Rutherford, 1934). Annual precipitation can be quite variable year to year (Wilson et al., 2013), but averages 477 mm (EC, 2012).

2.2 Study design

We selected 72 study wetlands belonging to one of four types. Natural reference sites were situated in protected areas like Elk Island National Park and the Blackfoot-Cooking Lake protected areas (Fig. 1). Agricultural wetlands are also natural in origin, with >50% land cover within a 500 m radius dedicated to agricultural activities including grazing, haying or row crops such as canola. In contrast, both stormwater ponds and stormwater wetlands were built by humans to retain stormwater. These created wetlands range in age, with the oldest constructed in 1978 and the newest in 2006. They are located in and around the City of Edmonton (Fig. 1), population 812,201 (StatsCan, 2012). These four wetland types thus differ in their exposure to stressors like road salt, the amount of surrounding impervious cover, the degree of active drainage management, and the landscape connectivity between wetlands. We therefore anticipate that these four wetland types span a gradient in condition, here listed from highest to lowest quality: natural reference, agricultural, stormwater wetlands, and stormwater ponds (Wilson et al., 2013).

We sampled the plant and bird communities at each of these wetlands, as well as water and sediment chemistry and seasonal changes in water level. This allowed us to characterize the biophysical values of each wetland type. In a subset of six wetlands, we carried out a survey of social values using three sets of samples of 20-34 individuals (73 participants in total) whom we took on day-long field trips to the sites (details below). By comparing the social and biophysical values perceived and described by study respondents at reference and agricultural wetlands and comparing these with responses to wetlands built by humans for stormwater control, we are able to evaluate the shift in classes and quantities of ecosystem services that occur when natural wetlands are replaced with stormwater management facilities.

2.3 Biophysical sampling

Sampling occurred in the summers of 2008 and 2009. Water depths were measured every six hours between May and September using HOBO depth data loggers. Basin morphometry, sediment characteristics and vegetation were sampled in July and August near peak biomass. Birds were sampled in June, during the breeding season.

In mid-summer we measured Secchi depth as an average of ten replicate measures taken in the open water zone of each wetland. Using a HACH multi-meter and probe, we measured conductivity, pH and turbidity at each site. We took laser level estimates of shoreline slopes and cored sediments (a composite of three replicate 10 cm deep and 5.72 cm radius cores) for laboratory analysis of total nitrogen (PN), total phosphorus (PP), total carbon (PC) and loss on ignition (%LOI). Further, we collected a water sample in July to measure total dissolved solids, phytoplankton chlorophyll-a (Chl-a), total suspended solids (TSS), alkalinity, dominant ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, $SO_4^{\,2-}$, Cl^-, $CO_3^{\,2-}$, and HCO_3^-), nutrients [soluble reactive phosphorus (SRP), nitrite and nitrate (NO_2^-+ NO_3^-), ammonia (NH_4^+), total dissolved nitrogen (TDN), dissolved organic carbon (DOC), total dissolved phosphorus (TDP), B, and Si], and metals (Fe and Al). Laboratory analysis was carried out at the University of Alberta Biogeochemistry Lab, following standard methods outlined in Rooney and Bayley (2010). Environmental data on hydrology, sediment and water chemistry and site morphology were used to calculate each site's Stress Score, an integrative measure of the level of human disturbance at a site (details in Rooney and Bayley, 2010). These data were also summarized in the principal components analysis described below.

Vascular plants in the wet meadow vegetation zone were sampled in six 1 m^2 quadrats at each site, in which all vascular plants were identified to species following Moss and Packer (1983) with taxonomy updated using the Integrated Taxonomic Information System database (ITIS, 2011). The percent cover of each species was then estimated to the nearest five percent. In addition, Robel pole measurements of aboveground biomass were taken and the width of the wet meadow zone was measured along three equally spaced transects across the moisture gradient (see Wilson and Bayley, 2012 for detailed methods). Data on vegetation in the wet meadow zone was used to calculate a plant-based index of biotic integrity (plant-IBI) score for each site, following the method described in Wilson and Bayley (2012). Metrics included in the plant-IBI were: 1) average width of the wet meadow zone; 2) percent cover of sedge species; 3) percent cover of native perennials; and 4) the Floristic Quality Assessment Index score (details in Wilson et al., 2013), which reflects the diversity of native species. For a general assessment of plant diversity, we calculated total species richness, the richness of native species, and the richness of obligate wetland species, with categorization derived from Moss and Packer (1983).

Breeding bird surveys were conducted multiple times at each site using the method outlined in Rooney and Bayley (2012). In brief, taxonomy followed the American Ornithologist's Union standards and sampling consisted of three auditory surveys (each comprised of two eight minute 50 m fixed-radius point counts) of songbirds and other passerines, spaced at least two weeks apart during May and June and restricted to the time between sunrise and 11:00. Bird data was used to calculate a bird-based index of biotic integrity (bird-IBI) score for each site, following Wilson and Bayley (2012). Metrics used to calculate the bird-IBI included: 1) the percent of total richness comprised of insectivores and granivores; 2) the percent of total richness comprised of ground nesting species; 3) the number of temperate migratory species; 4) the relative abundance of canopy foraging species; and 5) the number of passerine species. More generally, bird biodiversity was calculated as the total richness of passerines and the richness of obligate wetland species.

2.4 Public sampling

We administered a structured survey of 73 residents from Edmonton and the surrounding area. Groups of 20-34 people were taken on an eight hour field trip to three of our studied wetlands in September 2010: one natural reference and agriculturally impacted wetland, as well as one stormwatermanagement facility. The participants were selected by the University of Alberta Population Laboratory using random-digit dialing within the phone number prefixes of the

Beaverhills sub-watershed. Participants belonged to one of three equally represented groups: urban Edmontonians, suburbanites from nearby Sherwood Park (15 km from Edmonton), and rural residents of the outlying areas. Efforts were made to have similar respondent representation in age, gender and income categories as the population from which they were selected (note the entire region is dominated by residents who are in the upper middle income category). A slight bias exists in that our sample population was older than the resident population and more women participated than men. At each site, all participants were asked to fill out a structured survey to record their observations and identify ecosystem services provided by the wetland. Despite some missing ratings, in no case were there less than 69 scores per site/ecosystem service category. By way of introduction to the project, and prior to visiting the three types of wetlands, one of our team members provided a fifteen minute primer on the general ecosystem services of wetlands. The data featured here is drawn from this key question: “As you consider the wetland in front of you, what do you feel are the most important services it provides?” The services included biodiversity, existence, aesthetic, cultural heritage, water quality, flood control, erosion control and ground water recharge. Close-ended question response options included “not valuable”, “slightly valuable”, “valuable”, and “very valuable.” We combined the valuable and very valuable response categories, and compared the percentage of respondents who answered in these two categories against those who checked no value or slight value for each of the ecosystem services. Respondents were also offered the opportunity to note the desirable attributes (values) each of the wetlands bring to people, including components that are believed to exist but one cannot see. These responses were coded into categories of answers to see what answers were most common.

2.5 Biological Data analysis

The richness, stress scores and index of biotic integrity scores of the four wetland types were compared using General Linear Models with maximum likelihood estimation. If significant differences were detected among types, we carried out Tukey's Multiple Comparison tests for pair-wise comparisons with an experiment-wise error rate of 0.05. These univariate tests were carried out in SYSTAT v.13 (SYSTAT, 2010).

To explore the physicochemcial differences among wetland types in greater detail, we carried out principal components analysis (PCA) with the cross products matrix consisting of correlation coefficients among 33 environmental variables (some were log-transformed to improve normality) and created a joint plot with environmental variables overlain as vectors. Linearity of relationships and outliers were checked with bivariate plots. Skewness was checked and was inconsequential. Ordinations were carried out using PCORD v. 6 (McCune and Mefford, 2011).

3.0 RESULTS

3.1 Biophysical

Biological integrity was highest in natural reference wetlands based on both bird-IBI (GLM: $R^2 = 0.82$, $F_{3,68} = 46.74$, $p < 0.00001$) and plant-IBI scores (GLM: $R^2 = 0.84$, $F_{3,68} = 53.37$, $p < 0.00001$). Scores were slightly lower for agriculturally impacted wetlands and even lower for stormwater management facilities (Fig. 2). Interestingly, although mean scores tended to be lower for stormwater ponds than for stormwater wetlands, there was no significant difference in biotic integrity between the two created wetland types (Fig. 2).

Plant and bird richness results are less straight forward. There was no significant difference in the *total* number of species of plants in the wet meadow zones of the four wetland classes (GLM: $R^2 = 0.25$, $F_{3,68} = 1.53$, $p = 0.21$), but if only native or obligate wetland species are considered, there is a significant difference among types (GLM: $R^2 = 0.50$, $F_{3,68} = 7.54$, $p = 0.0002$; and $R^2 = 0.52$, $F_{3, 68} = 8.40$, $p = 0.00008$ for native and obligate wetland plant richness, respectively). In the case of both native and obligate wetland plants, richness is lower in stormwater ponds and stormwater wetlands than in natural reference wetlands (Fig. S2). Plant species found only in stormwater management facilities tended to be upland species, invasive weedy forbes or grasses that are common along roadsides. Birds presented a similar pattern when the difference in total richness of passerines among wetland types (GLM: $R^2 = 0.45$, $F_{3,68} = 5.74$, $p = 0.0015$) was compared with the difference in richness of obligate wetland bird species (GLM: $R^2 = 0.39$, $F_{3,68} = 4.02$, $p = 0.0108$), i.e., total passerine richness in reference and agricultural sites exceeded that of stormwater ponds, but not stormwater wetlands. Yet when only obligate wetland bird species are considered, richness in reference sites exceeds that in both types of stormwater management facility (Fig. S3).

An evaluation of mean environmental stress scores provides a window into possible causes of the observed biological differences among wetland types. Stress scores were significantly lower in natural wetlands than in stormwater management facilities (GLM: $R^2 = 0.87$, $F_{3,68} = 71.24$, $p < 0.00001$), although Tukey's multiple comparison analysis revealed that there was no detectable difference between the stress scores of stormwater wetlands and stormwater ponds (Fig. S4).

The environmental differences among site types are illustrated in more detail by the principal components analysis. We determined that a three axis solution was best, based on a scree plot of eigenvalues and by comparing eigenvalues to their associated broken-stick eigenvalues generated by 1999 iterations of a randomization test (McCune and Grace, 2002). Only the first two axes are presented as the third axis did not separate any of our four site types. Collectively, the first two axes explained 50.8% of the variance in our 33 environmental variables: 32.0% and 18.8% on axis 1 and 2, respectively. The joint plot (Fig. 3) reveals that axis 1 separates stormwater wetlands and stormwater ponds from reference and agriculturally impacted sites, which have greater seasonal drawdown and nutrient levels (both in sediment and water). In contrast, stormwater wetlands and stormwater ponds have steeper slopes. For example, the rise over 10 m run mean of 45 natural sites was 0.03 ± 0.03 standard deviation, compared with 0.12 ± 0.04 standard deviation for the 27 stormwater management facilities examined in this study (see also Table S1). Stormwater sites also tended to have higher nitrate-nitrite levels and chloride concentrations than natural wetlands, perhaps due to run off from roads or leaching from liners built with marine clays (Table S1). It is also worth noting that only naturally occurring wetlands have high TP and Fe (Table S1). Axis 2 separates natural sites from stormwater management facilities, but also separates reference sites from agriculturally impacted natural ones. Reference sites have lower concentrations of ions than the other three classes. They also have lower phosphorus, silicate and potassium levels in their water, which are more elevated in the agriculturally impacted sites than the stormwater wetlands. However, reference sites tend to have higher concentrations of nutrients in their sediment (Table S1).

Stormwater wetlands and stormwater ponds manage their water levels, resulting in artificial hydrologic patterns. Whereas natural sites typically experience more or less continuous drawdown throughout the summer, stormwater facilities have water maintained at a basic minimum level (Table S1), punctuated with sharp peaks indicating individual rainfall events. In

Fig. S5, which depicts representative wetland hydrographs, you can clearly see the collection of rainfall events in the example stormwater pond that produced a gentle increase in water level in a nearby natural wetland.

3.2 Sociological Results

Participants reported valuing many ecosystem services in the reference wetlands, agriculturally impacted wetlands and stormwater management facilities they visited. For the reference wetlands, over 80% of the respondents reported that they valued the services of biodiversity and groundwater recharge, which in fact fits closely with the biophysical assessment (Fig. 4). Given the high biophysical values observed in reference wetlands, and the rarity of reference wetlands within close proximity to urban areas, that reference wetlands were accorded high existence values also fits with the biophysical evaluation. Aesthetic and cultural heritage values in reference wetlands were ranked lower (30-40% of respondents valued these). It is notable that almost 90% of the respondents found value in the aesthetics of the stormwater pond, despite supporting few songbirds or other animals, and having a simple strip of mainly invasive, upland vegetation. Respondents were largely mistaken (57%) in the assumption that groundwater recharge was valuable in the impermeable stormwater ponds. Overall, respondents found almost as much value in contributions to water quality in the stormwater ponds (just over 68%) as they did in the reference wetlands (75%). Over 90% of our study participants recognized the flood control value provided by stormwater ponds, indeed the primary reason for their existence. Respondents found similar value in cultural heritage of the reference wetlands (40%) as the stormwater ponds (49%). Figure 10 shows “valued” scores from 59-97% for all categories. Their role in diversity and function were highlighted by the surrounding crop fields. Their existence was also highly valued. While there was relative homogeneity in percentages perceiving different values of the three wetland types, the rural respondents tended to report lower value for the goods and services of reference wetlands, and report higher biodiversity values for agricultural wetlands than urban and suburban respondents. Rural respondents also reported much lower biodiversity values for stormwater ponds than urban and suburban residents.

4.0 DISCUSSION

4.1 Biophysical values

We anticipated a gradient in wetland condition from near-pristine reference wetlands to stormwater ponds. Previous authors have found that stormwater wetlands provide enhanced biophysical values relative to stormwater ponds (e.g., Moore and Hunt, 2012). Thus, we were surprised to discover that the differences between natural and created wetlands produced essentially two categories, not a gradient. Although we found a trend of higher mean biotic integrity and biodiversity in stormwater wetlands than in stormwater ponds, when placed relative to naturally occurring wetlands, the difference becomes insignificant. This suggests that while stormwater wetlands were a marginal improvement over stormwater ponds, they are inadequate in the short term to compensate for the loss of natural wetlands, at least insofar as biodiversity and ecological integrity are valued. Research comparing the primary and secondary productivity of natural wetlands and stormwater management facilities (Woodcock et al., 2010) supports our conclusion that these two types of systems are functionally different on a fundamental level.

Biotic integrity of the bird and plant communities was lower in stormwater management facilities than in natural wetlands, although total species richness of plants was not. Natural wetlands support more native, obligate wetland plant species, but in stormwater wetlands and stormwater ponds, many of these are replaced by non-native or weedy upland species, such that the reductions in biodiversity are masked by an increase in the number of undesirable species. Similarly, the reduced richness of wetland-dependent birds in stormwater wetlands is somewhat masked by an increase in the occurrence of forest and grassland species, although total bird richness was significantly lower in stormwater management facilities than in natural wetlands. The key finding is that, although stormwater management facilities are home to a variety of plant and bird species, they are not supporting the full range of native, wetland-dependent species. Furthermore, the expected increase in biodiversity in stormwater wetlands over stormwater ponds is comparatively slight and not statistically significant. This pattern held constant across the range of ages of stormwater management facilities assessed in our study. Thus, the differences in richness and other biophysical values are not an artifact of wetland maturation; not at any management-relevant time scale.

We identified three major drivers for these differences in wetland biophysical values. First, natural wetlands have much gentler sloping shores and act more as pans than as deep tubs. In contrast, stormwater management facilities are commonly steep sided. Second, stormwater management facilities have altered hydrology, both in terms of timing and source of water. In particular, the stormwater management facilities are often lined with clay to prevent any connection to ground water and their water levels are often maintained at steady depth except for episodic flood peaks (Fig. S5). Third is landscape position: stormwater management facilities tend to be in peri-urban areas with higher population density, greater proportions of impervious land cover, and more exposure to roads and associated contaminants. These three drivers combine to reduce the biophysical values of stormwater management facilities relative to natural wetlands. An emergent concern is that these drivers are fixed and inflexible characteristics of stormwater management facilities. Engineering requirements dictate stormwater management facility slopes, and better mirroring of natural basin shapes directly compromises a facility's capacity to store stormwater. Similarly, clay liners are required to prevent contamination of ground water and to retain water within the facility. Certainly landscape positioning of stormwater facilities is non-negotiable. Thus, major advances in the ability of stormwater management facilities to mimic natural wetlands appear strictly limited and best management practices offer little hope of real improvements.

Stormwater management facilities are not entirely without biophysical value: they offer excellent flood control, perhaps to a degree unparalleled in natural wetlands. Yet flood protection is provided at the expense of biodiversity, ecological health, water quality, ground water recharge and other biophysical values. In the biophysical realm, stormwater ponds excel at what they were engineered to do: trapping flood water from precipitation, but they do little else.

Hydrographs typical of natural wetlands differ markedly from those typical of stormwater management facilities (Fig. S5). Previous research has highlighted the deviations in hydrology common to stormwater management facilities and the probable effects of such deviations on downstream water bodies (e.g., Burns et al., 2012). Furthermore, deviation from natural hydroperiods may disrupt other wetland services like nitrogen removal (Ishida et al., 2006) and affect greenhouse gas emissions (Mander et al., 2011). Such deviations will also impact local biotic communities. The characteristic zonation of wetland plant communities is particularly sensitive to fluctuations in water depth (e.g., Spence, 1982, Casanova and Brock, 2000), and zonation is an important driver of biodiversity in wetlands (e.g., Riis and Hawes, 2002). The steep shoreline slopes characteristic of stormwater management facilities would exacerbate the elimination of plant zonation. In fact, we observed that several stormwater ponds lacked a sedge-dominated wet meadow altogether.

We suspected that stormwater runoff would be contaminated with pollutants including salts, nitrates and metals (Casper, 1994, Farrell and Scheckenberger, 2003, Jartun et al., 2008); however, the primary chemical differences between stormwater management facilities and natural wetlands reflected differences in nutrient levels (Fig. 3, Table S1). Natural wetlands had higher nutrient levels, particularly in the sediment. The only exception was nitrate and nitrite levels, which were higher in stormwater management facilities. This is unsurprising as dissolved nitrogen is a common pollutant in urban run-off (e.g., Taylor et al., 2005). Previous authors have typically reported that stormwater is a source of nutrients and consequently of oxygen demand (e.g., Farrell and Scheckenberger, 2003). Our results, however, mirror those of Woodcock et al. (2010), who compared natural wetlands with stormwater management facilities of a similar age to those in our study. Like us, they found that natural wetlands have greater phosphate and organic matter but lower nitrate concentrations. Although atypically high nutrient levels are associated with declines in diversity (Lougheed et al., 2001), shallow open water wetlands in our region are naturally eutrophic and fertility is recognized as one of the primary environmental filters driving plant community structure (Weiher and Keddy, 1995). Thus, differences in fertility may be contributing to the observed differences in biodiversity and biotic integrity (Barko and Smart, 1986, Squires and Lesack, 2003). Theoretically, nutrients may accumulate as stormwater management facilities age, but we saw no evidence that older facilities had higher nutrient levels than newer ones despite our age range spanning nearly 30 years. Lower sediment nutrient levels in stormwater management facilities may create a positive feedback loop if they lead to reduced plant productivity, as the accumulation of organic matter is the net result of primary production minus decomposition. Regardless, the differences in organic matter content between the sediment of natural wetlands and stormwater management facilities will have important implications for ecosystem services like nutrient attenuation and carbon sequestration. E.g., Stewart and Downing (2008) found that phosphorus uptake only took place in stormwater wetlands with a high organic matter abundance, likely because of the essential role of bacteria and algal communities in nutrient removal and their dependence on organic matter (Stottmeister et al., 2003, Vymazal, 2007).

Nutrients, detritus, macroalgae and coarse woody debris are seen as undesirable in urban ponds for aesthetic reasons and also for engineering reasons of flood storage capacity and flows. However, in natural systems, these are all important contributors to food chains, habitat diversity and growth enhancers for microbial to macro-invertebrate ecosystem components. Many stormwater ponds have sediment and detritus traps that can be cleaned out periodically with heavy equipment. Some level of detrital settling can be expected, but shoreline and in-pond detrital production is likely to be lower, thus, reducing the role of deep detrital sediments and the use by benthic organisms.

4.2 Social values of wetland services

Due to the logistical constraints of the social values survey, we cannot evaluate whether differences in valuation of natural wetlands and stormwater management facilities made by the general public are statistically significant. They are, nonetheless, substantial. Unsurprisingly, stormwater management facilities are valued by the public principally in terms of flood protection. However, they were also valued in terms of their aesthetics. In the qualitative open ended question responses, the most commonly noted benefits of the various wetlands observed were the presence of shade trees, birds to view and park-like aesthetics such as landscaping and benches. They also considered the relative scarcity of insects as a positive attribute in stormwater management facilities.

The study participants valued stormwater management facilities highly in several respects, despite our findings that the biophysical value of stormwater management facilities are consistently lower than in natural wetlands. This may be due to the tendency for the public to place a much higher priority on the urban aesthetic and built-environment aspects of stormwater ponds where ecological services such as habitat for wildlife are visible (Gibbs 2000). Although respondents in our study could recite the names of many of the ecological services supported by wetlands, they were not often able to recognize the evidence of these services when directly viewing a wetland. When wetland attributes were not directly visible, respondents were less clear on their value. For example, over half the study participants ranked stormwater management ponds as valuable contributors to diversity maintenance and groundwater connection even though they were low diversity systems and largely isolated from groundwater by impermeable liners. Almost half of participants also considered stormwater management facilities valuable in terms of cultural heritage, even though they were recently built components of the environment. The authors were struck by the low aesthetic ranking (32%) of reference wetlands despite mixed species flocks of ducks flushing, multiple bands of complex vegetation and access along an active big game trail. Agricultural wetlands were valued as or more highly than reference wetlands for most services, reflecting the biophysical finding that they were not significantly impoverished relative to reference sites. Agricultural sites were seen as working wetlands that made substantial contributions to the site. Such wetlands often act as islands of biodiversity (Thiere et al., 2009) in a monoculture of crops, provide critical nutrient interception

(Dunne et al., 2005), are important habitat for waterbirds (Czech and Parsons, 2002) and are often sites of ground water recharge (Böhlke, 2002). Maintenance of wetlands within agricultural landscapes provides supporting and regulating services that augment agricultural productivity, including pollination services and natural pest control (Main et al., 2014), as well as a source of forage during drought years (Paoletti et al., 1996). We recognize that the perceived values of wetlands would likely vary based on the relative scarcity of certain kinds of wetlands in a particular region, and their cultural meaning and recreational uses.

4.3 Policy implications

Our goal in this study was not only to compare the biophysical and social values of natural wetlands with those of stormwater management facilities. We sought to characterize and contrast those differences to inform policymakers dealing with the issue of wetland compensation. Much of the evidence brought together here is known by regulators, consultants, developers and environmentalists but we have endeavoured to join the biophysical- spatial– social perception-policy implications in a way that addresses the challenges for science-informed policy. This includes social science on public perceptions and recognized values of different kinds of habitats. By addressing recent trends of wetland loss and replacement (e.g., with stormwater management facilities) greater scrutiny may be used in wetland policy decision-making.

The results of this research are particularly timely as Alberta has recently approved a new Provincial Wetland Policy (GoA, 2013) founded on a hierarchy of avoidance, minimization and finally replacement (i.e. compensation), where wetland impacts from development are deemed unavoidableUnder the new policy, stormwater management facilities will be eligible for partial wetland replacement credit, meaning that developers destroying natural wetlands will be charged a reduced wetland replacement fee if they incorporate stormwater wetlands or ponds into their development (Thorsten Hebben, Alberta Environment and Sustainable Resource Development, pers. comm.). Under the Interim Wetland Policy, most jurisdictions did not provide compensation credit for stormwater management facilities but this is a perpetual point of discussion and negotiation, not a hard and fast rule. Our results suggest that because stormwater management facilities, even stormwater wetlands, fail to provide the same biophysical values as natural wetlands they should be down-weighted as compensation credits. Although stormwater management facilities are designed to provide flood control and attenuate sediments, natural wetlands also provide these services (e.g., McAllister et al., 2000, Vellidis et al., 2003). Yet natural wetlands provide an additional suite of important hydrologic, biodiversity, habitat and ecological integrity values that stormwater management facilities do not provide. Granting compensation credit for stormwater management facilities may lead to the replacement of natural wetlands supporting high biophysical value with stormwater wetlands or ponds of low biophysical value, resulting in a net loss of biophysical value across the province. Our biophysical findings do not support the use of stormwater management facilities for full compensation credit.

A redeeming feature may be that, under the new policy, a range in mandated compensation ratios allows the government to afford partial credit by varying the area of wetland creation or restoration required for every hectare of natural wetland destroyed on the basis of their relative values. For example, up to 10 hectares of low quality wetland (grade D) may be required to replace a single destroyed hectare of high quality wetland (grade A). We suggest that the public appreciates the value of both natural wetlands and stormwater management facilities, and values certain natural wetland services above others. While the new Alberta Wetland Policy assigns grades to wetlands based on biophysical values and social values, our study suggests that apparent trade-offs between biophysical and social values may impede our ability to discriminate high from low value wetlands by lumping all wetland grades in the middle range. For example, if social values such as cultural heritage or aesthetic values are lower in natural wetlands than in stormwater management facilities, then averaging biophysical and social values may contribute to continued permitted loss of natural wetlands because the public perception is that reference wetlands provide little cultural heritage or aesthetic value.

To successfully protect wetlands and their ecosystem services, it is not enough that the policy be based on sound science: its practical ability to address wetland protection, especially in the implementation procedures, must also be comprehensible and supported by the public, especially with those whose compliance is necessary (Clare et al., 2011). Our results indicate that the general public does value wetlands, despite poor practical skills at identifying the ecosystem services different types of wetlands provide. The public undervalues the ecosystems services of reference wetlands compared to stormwater management facilities, which leads us to argue that the public understanding of wetland values continues to evolve, and public use and presence in wetlands is limited. This limited presence of people in natural wetlands may diminish the social values in comparison with those of more frequently visited wetlands in urban and suburban green and forested places where people highly value their rare presence (Hugh, 1994) and often fight to protect them (Palmer and Smardon, 1989).

There may be a number of efforts that can enhance public understanding of wetlands, such as better community based mapping and planning around wetland resources with long term ecosystem consequences in mind, and corresponding zoning and other development rules to avoid further wetland destruction. Further, an education and outreach campaign aimed at helping the general public develop rules of thumb regarding the kinds of ecosystem services associated with agricultural, natural, and stormwater wetlands, would allow better substantiated trade-off decisions on which wetlands to conserve or construct. The 2013 policy, amid much controversy, specifically allows some portion of compensation payments to be used for public education, so a mechanism now exists to expand the public understanding of wetlands in Alberta.

Developers must build stormwater management facilities to manage flooding risk in new developments. They often seek to count stormwater management facilities towards any required compensation for the destruction of natural wetlands related to their development. Providing partial compensation credit to developers for efforts to maximize the biophysical value of stormwater management facilities would provide a tangible financial incentive to innovate stormwater management facility design. Over time, this may help reduce the loss of wetland values currently taking place as a result of urban and suburban developments. We suggest that gentler shoreline slopes and management of hydrology to better mimic seasonal drawdowns typical of natural wetlands would potentially improve conditions for wetland biota. However, without adoption of a more sophisticated flow-regime management approach (sensu Burns et al., 2012), such modifications to stormwater management facility design would reduce their efficacy at performing their primary function: retaining stormwater, and require a larger footprint in the middle of a development area, thereby increasing opportunity costs to developers. Even with the best possible design, there are certain ecosystem services that stormwater management facilities are incapable of providing in an urbanized context, such as ground water recharge, which would be in conflict with city drainage goals and homeowner's dry basements. Furthermore, the aesthetic and recreational values attributed by the general public to stormwater management facilities are not likely to be enhanced by increased naturalness unless a substantial public education program is undertaken. At present, we contend that stormwater management facilities should only be permitted as compensation for the destruction of low quality natural wetlands and that only partial compensation credit should be afforded for their construction.

5.0 CONCLUSIONS

Our study aimed to integrate an assessment of the biophysical values of natural wetlands and stormwater management facilities with an evaluation of perceived social values. This combination of assessment approaches led to surprising results, namely that perceived social values of stormwater wetlands diverge from measured biophysical values. Perhaps this discrepancy is the result of difficult-to-observe traits like ground water connectivity and seasonal draw down, or replacement of native and wetland obligate species with non-native or upland invaders. To a casual observer, these differences are invisible, or at best, likely subtle. Even trained observers may require multiple site visits to detect them. This raises concerns in relation to reliance on citizen scientists to monitor wetland values or inform the social value of an individual wetland. Public perception clearly requires training in the detection of such subtle but fundamental wetland traits. A more realistic way to incorporate social wetland values into a wetland policy may be to do this at the jurisdictional planning level, where citizens can engage with scientists and land use experts in that region to identify the ways in which wetlands are currently valued in relation to ecological goods and services, use, appreciation and landscape features. Development pressures expected in the region could be taken into account in such planning, thereby encouraging proactive plans to protect the wetlands of greatest value and scarcity.

Another important conclusion we draw from our findings is that agriculturally impacted wetlands provide more value than anticipated, and they should not be assumed to be of poor biological integrity or biophysical value simply because of their surrounding land use. This has substantial importance as scientists and land managers rely increasingly on land use to predict wetland values. Remote sensing may reveal that extensive agricultural activity is taking place adjacent to a wetland, but wetlands are resilient systems and biophysical values are not necessarily compromised. Site visits by trained personnel remain the best way to measure biophysical values in potentially impacted wetlands.

While we were surprised to see so little difference between agriculturally impacted wetlands and natural reference ones, the converse was true with respect to stormwater wetlands and stormwater ponds. Despite research suggesting that stormwater wetlands represent a major improvement over stormwater ponds, we found that this difference in quality is inconsequential when the biophysical values of stormwater management facilities are placed on the same scale as natural wetlands. Unfortunately, the major drivers of the difference in biophysical values between stormwater management facilities and natural wetlands appear to derive from fixed components such as basin morphology, basic hydrology and landscape position. Further, these differences in fixed components are inherent to the stormwater retention function of stormwater management facilities. Thus, we see little opportunity for stormwater management facilities to truly mimic the biophysical values provided by naturally occurring wetlands. This reinforces the maxim that wetland conservation should always trump compensation or restoration.

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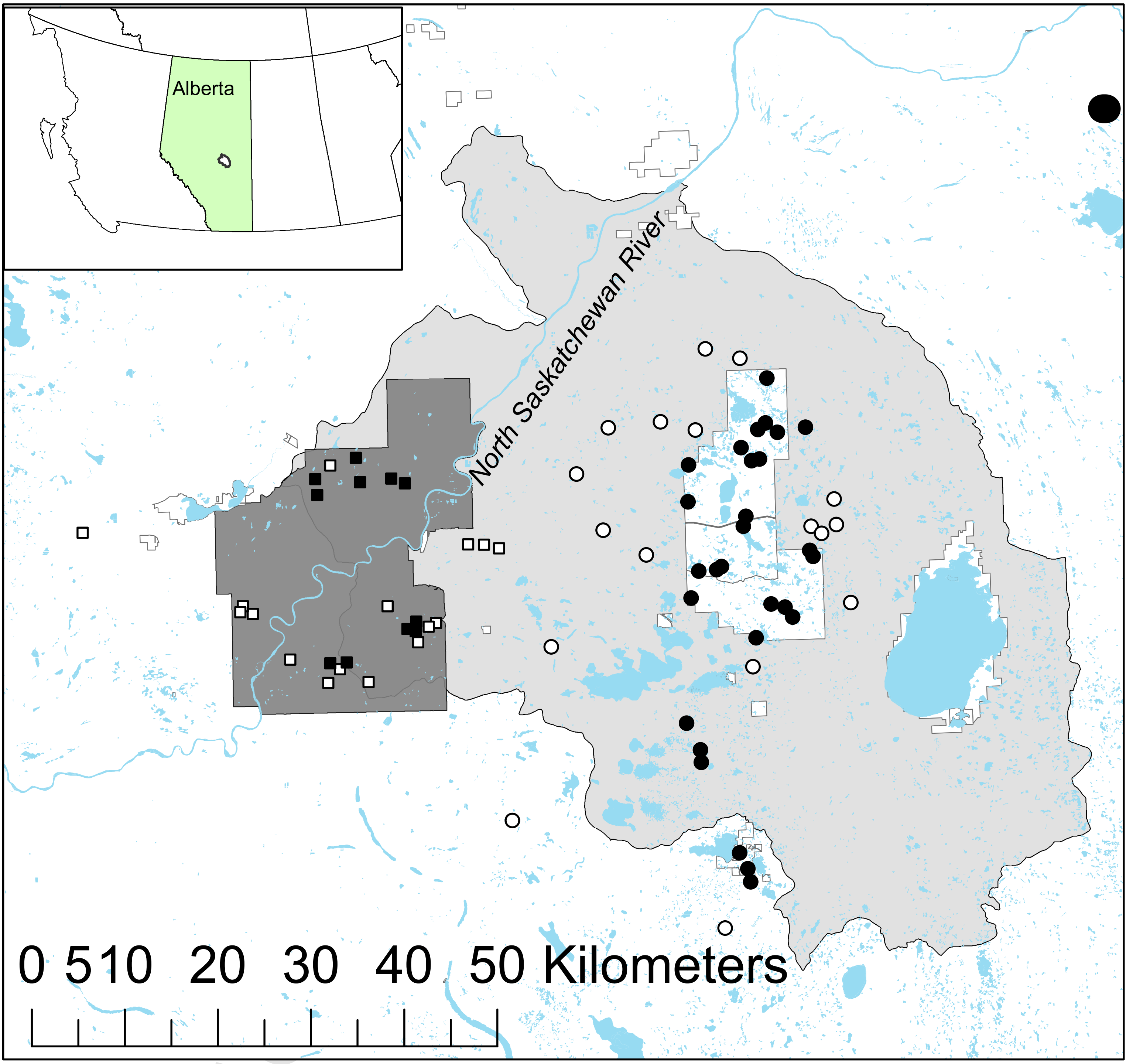
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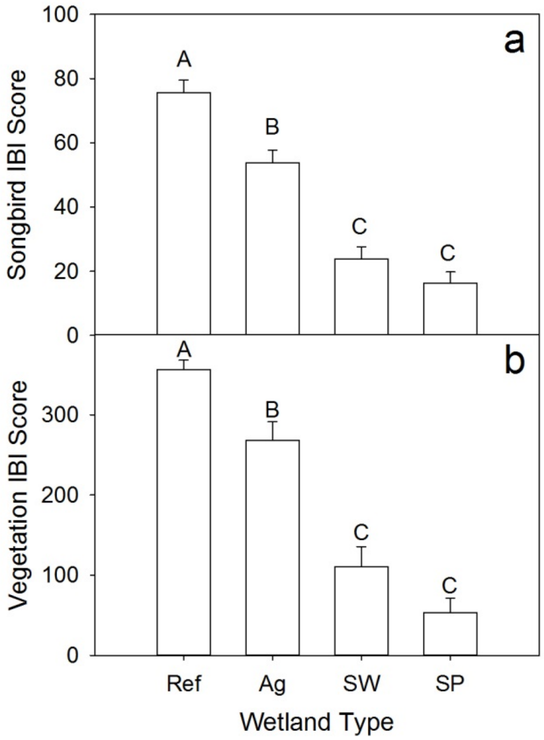

Fig. 2. Biotic integrity. Comparison of mean index of biotic integrity scores for the four types of wetland in terms of their bird-IBI (a) and plant-IBI scores (b). The types of wetland include reference sites (Ref), agriculturally impacted sites (Ag), stormwater wetlands (SW) and stormwater ponds (SP). Letters denote groupings based on Tukey's Multiple Comparison testing. Error bars represent standard error.

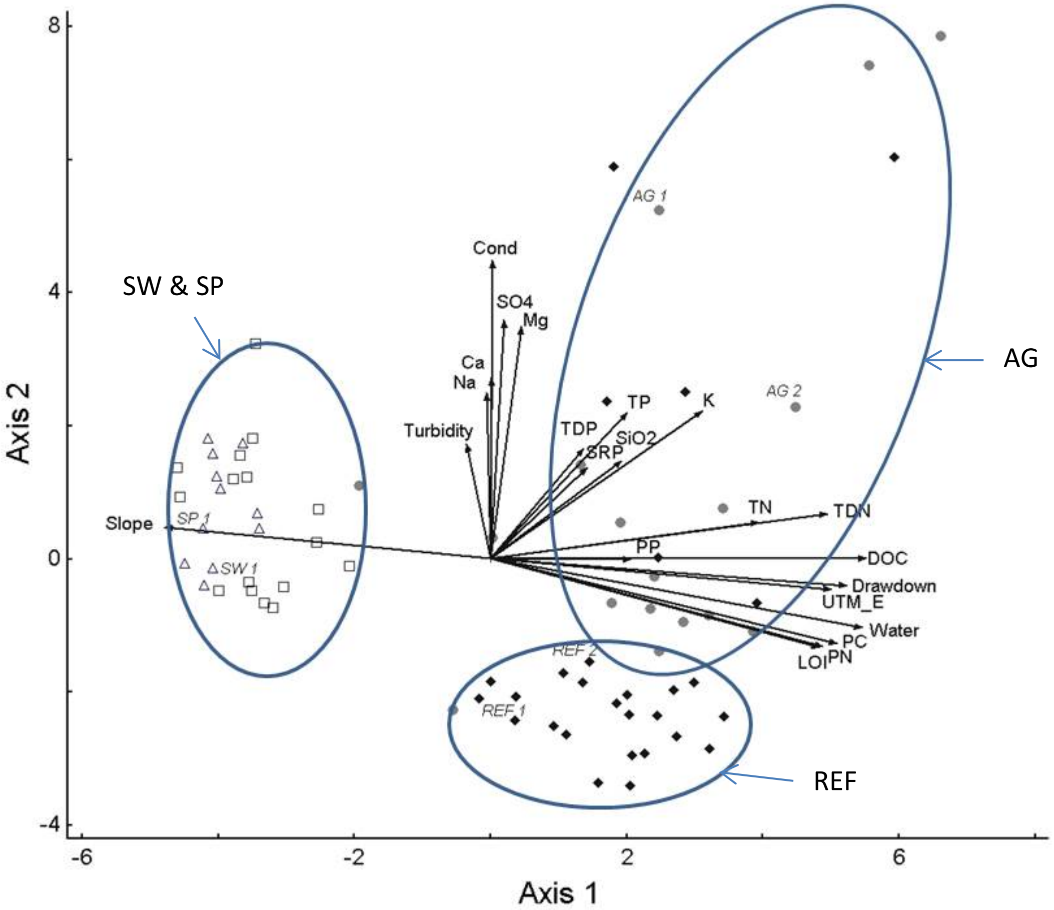

Fig. 3. Physiochemical characterization. A joint-plot summarizing variance among the 72 wetlands in terms of 33 environmental variables along the first two principal components axes, with points positioning sites in ordination space: diamonds are natural reference wetlands (REF), dots are agriculturally impacted wetlands (AG), hollow squares are stormwater wetlands (SW), and hollow triangles are stormwater ponds (SP). Vectors indicate the degree of correlation between ordination axes and environmental variables (R^2>0.25 with at least one ordination axis for all variables depicted). The sites visited during public surveys are labelled in italics. Clustering of sites of different type is illustrated with circles, labelled to indicate wetland type.

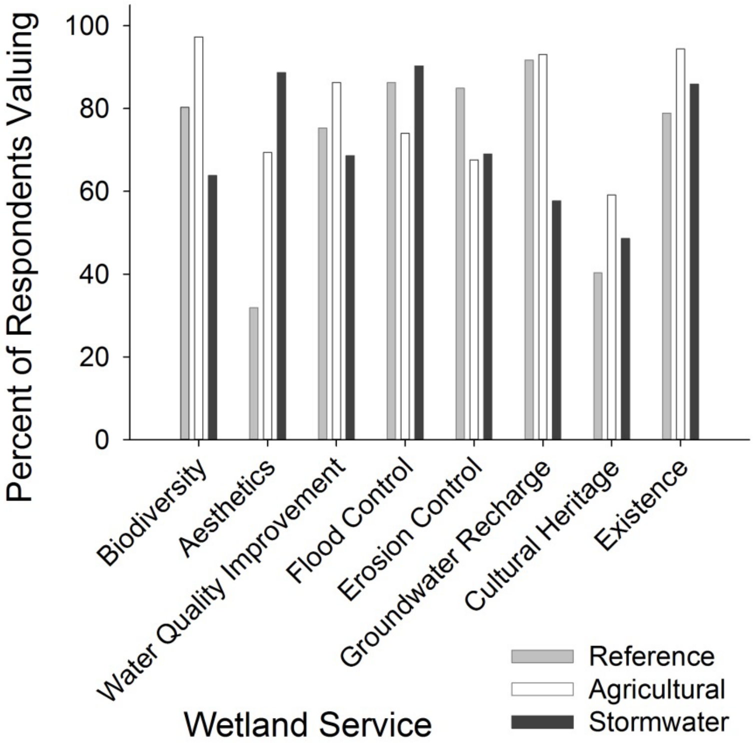

Fig. 4. Perceived social values. Percent of survey participants responding that a given service is valuable or very valuable in three types of surveyed wetlands: grey bars are reference wetlands, white bars are agriculturally impacted wetlands, and black bars are stormwater management facilities. In total 73 members of the public participated in the survey, with a minimum of 69 reporting on each service for each wetland type.

Replacing natural wetlands with stormwater management facilities: biophysical and perceived social values

SUPPLEMENTARY INFORMATION

Table S1. Wetland type comparison. Differences among naturally occurring wetlands, both agriculturally impacted and relatively undisturbed reference ones, and stormwater management facilities, both stormwater wetlands and stormwater ponds.

Characteristic*	Reference	Agricultural	Stormwater wetland	Stormwater pond
Origin	Natural post-glacial landscape feature	Natural post-glacial landscape feature	Constructed	Constructed
Intended purpose	Natural	Natural	Control flood water, attenuate sediment & mimic appearance of natural wetlands	Control flood water & attenuate sediment
Landscape context	Parks and protected areas	Grazed and cropped lands	Urban and suburban developments with higher population density, greater impervious cover, and more roads	Urban and suburban developments with higher population density, greater impervious cover, and more roads
Groundwater connectivity	Variable, depending on surficial geology	Variable, depending on surficial geology	Isolated, typically with clay liner	Isolated, typically with clay liner
Slope (average rise over 10 m run, n = 3)	0.02	0.04	0.11	0.13
Drawdown (seasonal drop in water depth, m)	0.357	0.353	0.079	-0.003
Hydrologic pattern	Large spring inundation and gradual summer-long drawdown	Large spring inundation and gradual summer-long drawdown	Water levels held constant with sharp peaks in response to	Water levels held constant with sharp peaks in response to

			individual rainfall events	individual rainfall events
Sediment nutrients (N, C % by-weight)	2.00, 23.50	1.78, 20.55	0.28, 4.25	0.11, 2.60
Turbidity (NTU)	109.45	317.86	322.69	447.54
Chlorophyll-a (µg L^{-1})	78	106	9	32
Ammonia (µg L^{-1})	236	698	84	100
Nitrate & nitrite (µg L^{-1})	2.3	4.1	91.2	24.7
Soluble reactive phosphorus (µg L^{-1})	82.7	182.2	30.0	43.8
Total phosphorus (µg L^{-1})	380.3	735.7	101.8	155.1
Iron (mg L^{-1})	0.13	0.12	0.05	0.03
Dissolved organic carbon (mg L^{-1})	48.36	41.43	14.66	10.45
Chloride (mg L^{-1})	10.09	47.10	132.51	65.89
Number sampled	28	17	16	11

* Values are the average for all wetlands sampled of each wetland type.

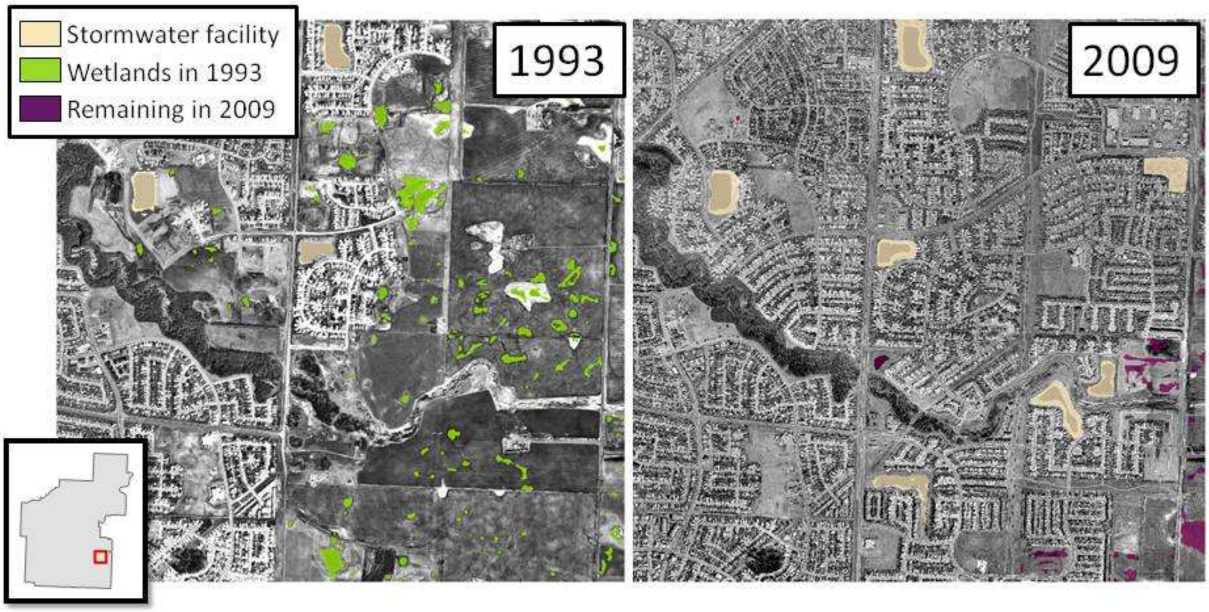

Fig. S1. Continuing wetland loss. Visual demonstration of the replacement of natural wetlands with stormwater management facilities. Air photos of the same area in the City of Edmonton (inset) are presented from 1993 and 2009. Wetlands present in 1993 are highlighted as green: those remaining in 2009 are in purple. Stormwater management facilities are in peach. Image see Clare and Creed (2014).

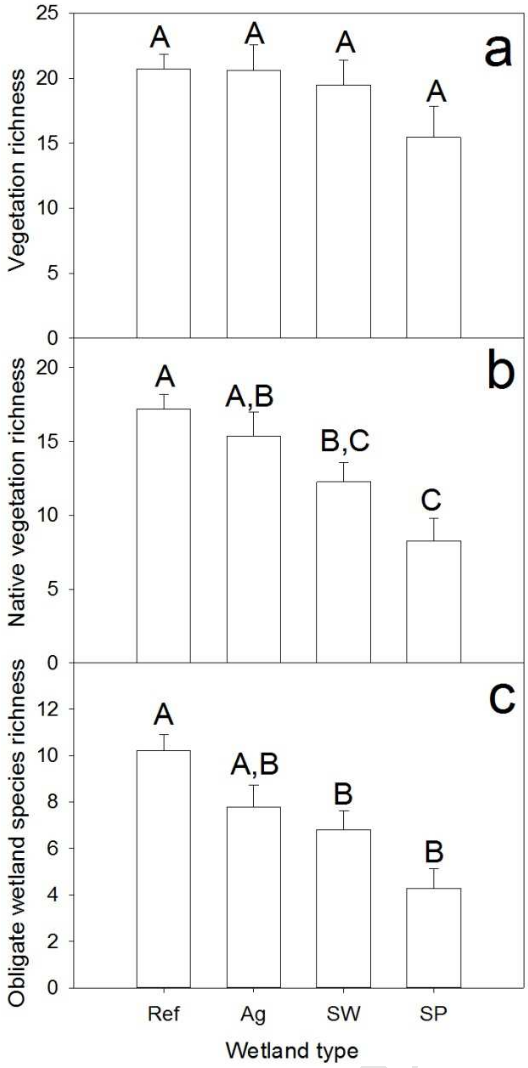

Fig. S2. Plant diversity. Plant diversity compared among natural reference (Ref), agriculturally impacted (Ag), stormwater wetlands (SW), and stormwater ponds (SP). Letters above the bars indicate Tukey's groupings based on multiple comparison testing and error bars represent standard error. Diversity is represented as total species richness (a), the richness of native species (b), or the richness of obligate wetlands species (c).

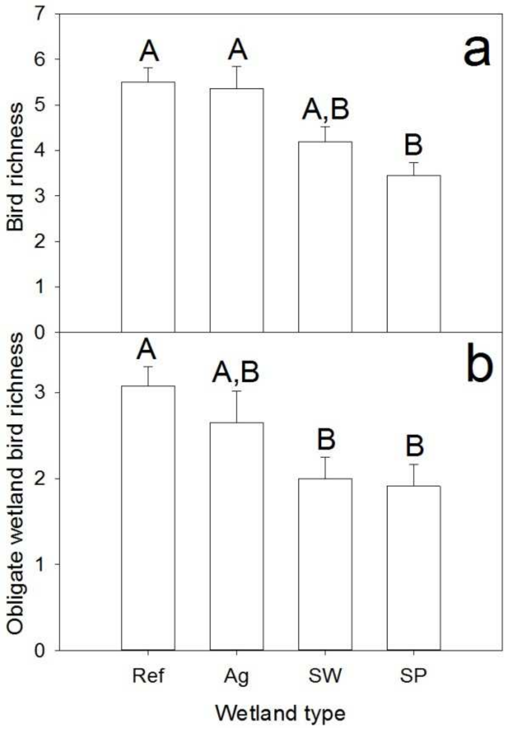

Fig. S3. Bird diversity. Diversity (species richness) of passerines compared among natural reference (Ref), agriculturally impacted (Ag), stormwater wetlands (SW), and stormwater ponds (SP). Letters above the bars indicate Tukey's groupings based on multiple comparison testing and error bars represent standard error. Diversity is represented as total species richness (a) or the richness of obligate wetlands species (b).

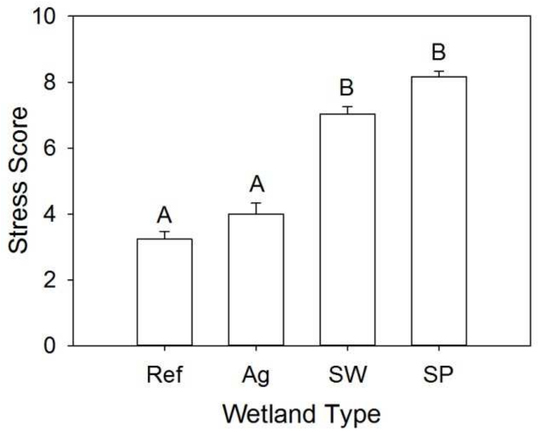

Fig. S4. Stress scores. An among-type comparison of stress scores, an integrative measure of the level of environmental stress acting on a site for reference wetlands (Ref), agriculturally impacted sites (Ag), stormwater wetlands (SW), and stormwater ponds (SP). Letters indicate Tukey's groupings based on post-hoc multiple comparisons testing and error bars represent standard error.

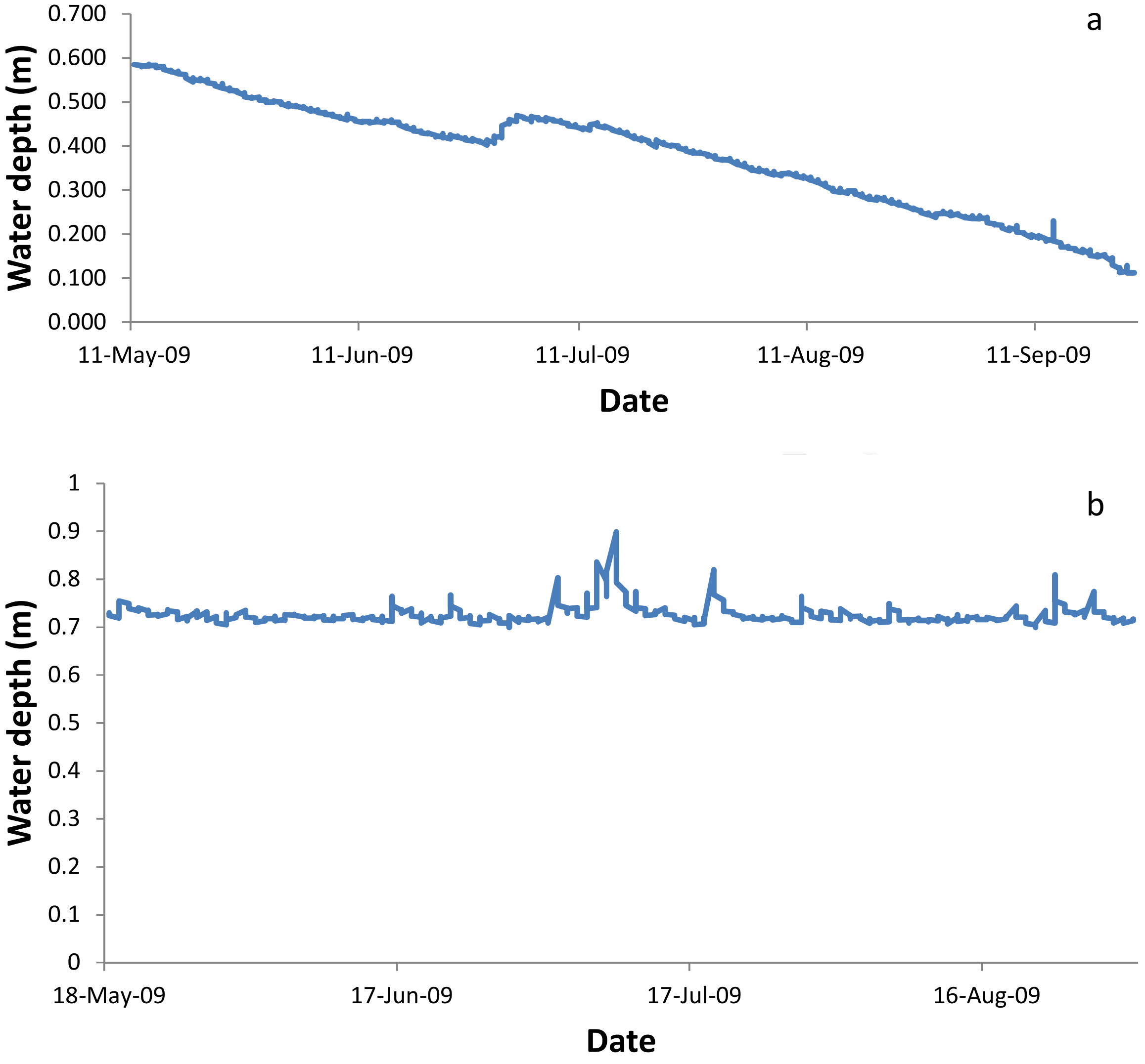

Fig. S5. Two hydrographs: a) represents changes in water level over the course of the sampling season at a natural reference wetland in Elk Island National Park; b) represents changes in a typical stormwater pond over the same period.

REFERENCES

Clare, S. and Creed, I. (2014) Tracking wetland loss to improve evidence-based wetland policy learning and decision making. Wetlands Ecology and Management 22(3), 235-245.