Ecological Engineering xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

# A qualitative assessment tool for ecologically based stormwater systems

Trisha Moore[a], Stacy L. Hutchinson[b,*], Reid David Christianson[c]

[a] North Carolina State University, Biological and Agricultural Engineering, Campus Box 7625, Raleigh, NC 27695, United States
[b] Biological and Agricultural Engineering, 129 Seaton Hall, Kansas State University, Manhattan, KS 66506, United States
[c] Extension Program Specialist, Agricultural and Biosystems Engineering, Iowa State University, 210 Davidson Hall, Ames, IA 50011, United States

ARTICLE INFO

*Article history:*
Received 1 October 2010
Received in revised form 28 February 2011
Accepted 22 March 2011
Available online xxx

*Keywords:*
Ecological assessment
Stormwater management

ABSTRACT

A qualitative ecological health assessment was developed for application to ecologically designed stormwater systems to enhance post-implementation monitoring and maintenance efforts. The assessment was based on qualitative soil and rangeland assessments from the literature. The assessment was applied to two stormwater systems in northeastern Kansas, both of which were designed after the tallgrass prairie ecosystem. One of the sites was a stormwater basin with well-established prairie grasses; the other was reseeded with prairie grasses at the beginning of the study period. With the difference in vegetation age at the sites, the sensitivity of the assessment to vegetative and ecological maturity could be ascertained. An overall health score was determined based on observations of the vegetation, soil health, erosion indicators, and fauna at the site. In general, ecological health scores at the older, more established site were higher, indicating that the ecological health, and presumably the functionality of the system, improves over time. Observations at both sites point to the need for maintenance regimes that will ensure the continuance of ecosystem processes. Initial results indicated that the application of an ecological health assessment such as the one developed for this study could help in making post-installation monitoring efforts more successful.



## 1. Introduction

In light of regulatory and civic pressures to protect aquatic resources within and downstream of urban areas, approaches to urban stormwater management have begun to change (Debo and Reese, 2003). Municipalities across the country are looking to ecologically engineered stormwater systems to meet their stormwater quality discharge requirements and reduce stream channel degradation caused by excessive post-development flows. As defined by Henry T. Odum (1962), ecological engineering refers to "those cases where the energy supplied by man is small relative to the natural sources but sufficient to produce large effects in the resulting patterns and processes." Accordingly, ecologically engineered stormwater systems are designed to enable ecosystem functions-including infiltration and pollutant attenuation by soils, evapotranspiration by vegetation, and nutrient cycling by vegetation and soil biota- to manage stormwater quality and quantity.

Throughout Northeast Kansas and much of the mid-continental United States, ecologically engineered stormwater management practices have been designed after the tallgrass prairie ecosystem, which, prior to the plow and urbanization, was the dominant landcover in the region. Multiple studies have demonstrated the potential of stormwater systems vegetated with tallgrass prairie species to reduce peak runoff rates and volumes (Culbertson and Hutchinson, 2004; Holman-Dodds, 2006). In addition to their extensive root systems that enhance the infiltration properties of the soil, these robust prairie grasses are also adapted to the region's climatic patterns, enabling them to survive intense storm events followed by extended periods of drought. Studies have shown that prairie grasses can be very effective in intercepting rainfall before it reaches the soil, thus reducing runoff volume. For example, Weaver and Rowland (1952) found that thick stands of big bluestem (Andropogon gerardii) were capable of intercepting 97% of the rainfall during very light showers and about 66% during storms in which 3 cm to 4.5 cm (1.2–1.8 in.) of rain fell. Stated in other terms, a well-developed stand of big bluestem with fully developed foliage may intercept over 1.3-cm of water per acre when 2.5-cm of rain falls in 1 h (Weaver and Rowland, 1952). Infiltration rates under well-developed prairie grasses are also impressive. In a study comparing infiltration rates under the tallgrass prairie native big bluestem and Kentucky bluegrass (Poa pratensis), a shallower-rooted cool-season grass which has been domesticated for use in lawns, big bluestem exhibited infiltration rates up to 480% greater than bluegrass (Weaver and Rowland,

* Corresponding author. Tel.: +1 785 532 2943; fax: +1 785 532 5825.
*E-mail address:* sllhutch@ksu.edu (S.L. Hutchinson).

0925-8574/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecoleng.2011.03.021

1952). By virtue of their ability to substantially improve infiltration and reduce surface runoff, native prairie grasses are ideal candidates for ecologically designed stormwater systems in the Midwest.

There are several challenges to the long-term maintenance and function of ecologically designed stormwater systems, such as those modeled after the tallgrass prairie ecosystem in the Midwest. One of these challenges is the proper assessment of these systems, which is critical both to improving design standards and developing proper maintenance regimes. Typically, the same metrics used to assess traditionally designed stormwater structures are applied to ecologically designed systems and include measures of both water quality (such as total suspended solids, contaminant concentrations, and BOD) and water quantity (such as peak flow and volume reduction). However, since the performance of ecologically designed stormwater systems hinges upon ecosystem processes occurring within the system – including sedimentation, infiltration, sorption, biological degradation, nutrient transformation, and evapotranspiration – the overall health of the ecosystem should also be considered when assessing the performance of these systems. While physical and chemical indicators such as water quality and quantity are important assessment tools as they measure the effectiveness of stormwater control, additional indicators which integrate the biological and ecological aspects of the system are needed to provide a more complete picture of overall health and performance potential of ecological stormwater systems (Watzin and McIntosh, 1999).

Measuring ecosystem health, or the ability of an ecosystem to maintain its organization and autonomy over time while being resilient to stress (Doran and Parkin, 1996), presents challenges of its own. Many attributes of ecosystem health, such as the integrity of nutrient cycles, energy flowpaths, and resilience, are difficult to directly measure (Pyke et al., 2002). To counter this challenge, ecological and biological indicators representing components of these difficult-to-measure attributes have developed since the late 1980s to aid in assessing ecosystem health across a wide spectrum of both aquatic and terrestrial ecosystems (Jørgensen et al., 2005). Indicators can be as simple as a general presence or absence of a species, or as complex as detailed energy balances (Jørgensen et al., 2005). Due to the inherent complexity and heterogeneity of natural systems, ecologists recognize that it is not feasible to use a single indicator, or even a few, as a general assessment of ecosystem health. Rather, sets of indicators tailored to a particular ecosystem are used in concert to assess ecosystem health (Jørgensen et al., 2005).

The objective of this study was to develop an ecological health assessment tool for use in ecologically designed stormwater systems to complement traditional hydraulic and chemical analyses. The target users of this assessment tool are municipal stormwater and public works employees who are typically responsible for monitoring and maintaining these systems. Keeping in mind the limited time, finances, and ecological backgrounds of most city stormwater programs, the goal of the assessment tool developed for this study was to provide users with an easy-to-use and inexpensive means of quickly assessing the general health of the system to gauge performance potential and guide maintenance decisions.

## 2. Methods and materials

### 2.1. Development of the ecological assessment rubric

Using qualitative assessments already developed for soil and rangeland health as a guide, an ecological assessment rubric was developed for application to stormwater management systems designed after prairie ecosystems. The rubric was broken into four main categories: vegetation health, soil structure, soil erosion, and faunal health. Each of these categories contained three to four indicators which were given a score of one through four, with one being poor, two being fair, three being good, and four being excellent condition. These scores were assigned based upon how the conditions at the site compared with the conditions described in the rubric for each ranking. Indicators within each category were chosen based on their relevance both to ecosystem health and desired function of a stormwater management system, namely to soil stability, hydrologic function, and biotic integrity. To determine the overall score for each category, the individual scores assigned to each indicator within the category were summed. A final rating for overall ecosystem health was determined by summing the scores for each of the four categories. A diagram of the rubric developed for this study is presented in Fig. 1 to graphically illustrate the indicators within each category and their contribution to the overall health score.

It should be noted that the scoring system used for this assessment rubric assumed that all indicators contribute equally to the overall health of the ecosystem and did not account for the relative importance of one indicator to another. Still, an equally weighted rubric was selected as the best model for the assessment developed for this study as it is simple and its use is supported by similar assessments in the literature which report satisfactory response despite being equally weighted (Manske, 2002; Romig et al., 1996).

The following sections describe each of the indicators included in the rubric in greater detail and provide reasoning for their inclusion in an assessment for the function of an ecological stormwater system. Descriptions of the "Excellent" and "Poor" ranking are given for each indicator to illustrate the full range of possible conditions. The complete ecological health rubric developed for this study includes descriptions for the "Good" and "Fair" rankings as well, and is displayed in Table 1.

#### 2.1.1. Plant health

The category for plant health considered plant density, diversity, and overall vigor. In an ecological stormwater system, vegetation health is perhaps one of the easiest characteristics of the system to observe. As in most other vegetated systems, establishing a dense stand of vegetation is extremely important in order to prevent soil erosion from the system. In addition to holding soil in place, vegetation also helps to prevent the occurrence of soil sealing and the formation of soil crusts by protecting soil from the impact of raindrops (Holman-Dodds, 2006). An additional advantage of closely spaced vegetation in vegetated stormwater systems is that dense vegetation slows the flow of water moving through the system better than fragmented clumps of vegetation, thus improving the removal of suspended sediments. The rubric developed for this study assessed density on the basis of plant distribution and the amount of soil surface exposed. Systems in which plants were distributed such that less than 20% of the soil surface was exposed received a score of "Excellent" (4); a rating of "Good" (3) was assigned to systems with 20–40% exposed soil; a rating of "Fair" (2) was assigned to systems with 40–60% exposed soil; and those with a clumped or fragmented distribution pattern which left over 60% of the soil surface exposed received a ranking of "Poor" (1). Percent cover partitions for the plant distribution category were based on a similar partitioning scheme set forth by Manske (2002) for rating plant distribution in rangeland health assessments.

In addition to plant density, plant diversity is another important component of vegetation health. Diversity is desirable within the tallgrass prairie ecosystem because diverse systems are usually more resilient against stressors such as the introduction of disease, pests, or toxic chemicals, and unfavorable climatic conditions (Collins et al., 1998). In the case of prairie ecosystems, plant biodiversity is an important feature of ecosystem function. Differ-

Please cite this article in press as: Moore, T., et al., A qualitative assessment tool for ecologically based stormwater systems. Ecol. Eng. (2011), doi:10.1016/j.ecoleng.2011.03.021

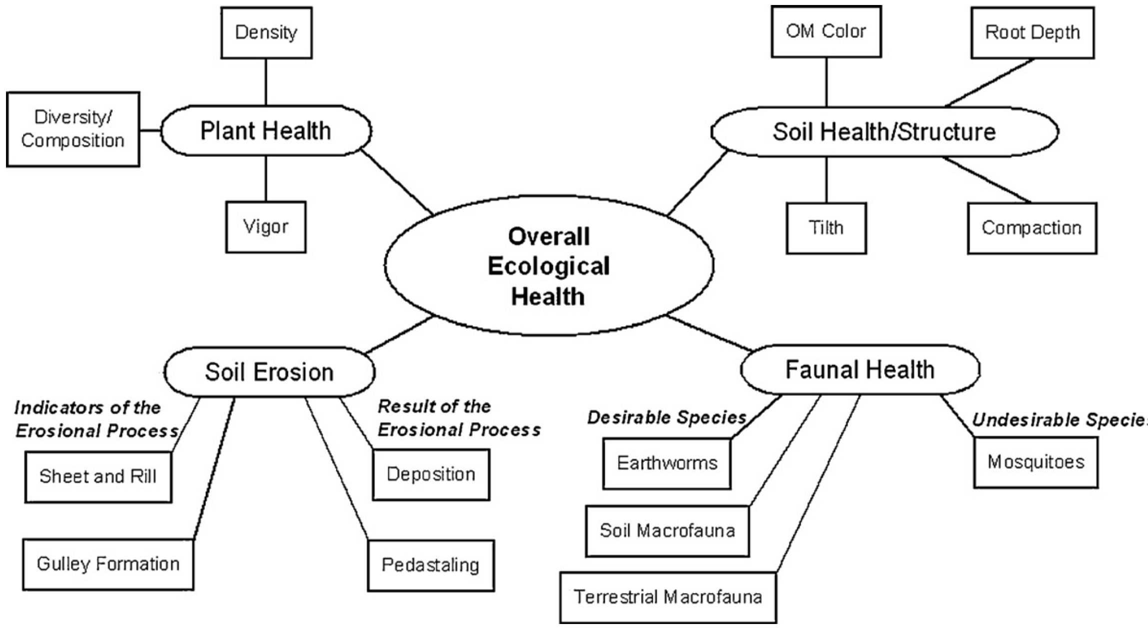


**Fig. 1.** Diagram of health assessment rubric developed for application to ecological stormwater systems.

ent species of grasses and forbs exhibit different rooting structures to extract water and nutrients from different depths within the soil profile (Weaver, 1958). Such diversity in root structure is a desirable feature for ecological stormwater systems because it allows the soil profile to be dried out more completely between rainfall events thus increasing the storage capacity of the soil for the next storm. Plant diversity is also important when considering the hydrologic aspects of a vegetated stormwater system as some plants tolerate frequent inundation with water while others flourish in drier environments. The aesthetic appeal of a diverse plant community offers another advantage to vegetated stormwater systems. For example, the various heights, colors, and flowering parts of different grasses, forbs and wildflowers can be exploited to design a stormwater system that is both functional and pleasing to the public eye. For the purposes of this assessment, "Excellent" sites are those with a diverse plant community with no invasive species while sites with greatly restricted diversity or many undesirable or invasive species was considered "Poor."

While a diverse vegetative community is desirable, not all plants are as desirable as others. In the case of prairie ecosystems, invasive species such as *Sericea lespedeza* can crowd out native grasses and transform the system into a monoculture (Ohlenbusch et al., 2001). In a stormwater system designed after a prairie ecosystem, other less desirable plants include weedy annuals such as foxtail (*Setaria spp.*), crabgrass (*Digitaria spp.*), and stinkgrass (*Eragrostis cilianensis*). These grasses have a shallow root system and therefore contribute minimally to improving soil structure or infiltration properties. Shallow-rooted plants are also unable to access water once it has percolated below the top few inches of soil, rendering these plants relatively ineffective at drying out deeper portions of the soil profile between rain events. The desired plant composition will depend upon both ecosystem type and the goals of the system. In the case of prairie ecosystems for which this assessment rubric was developed, a ranking of "Excellent" was assigned for systems with a diverse plant community of grasses, forbs, and wildflowers with no invasive species. A "Poor" ranking was given to systems with relatively little diversity and many invasive or undesirable species such as weedy annuals.

The final indicator of plant health used in the rubric was the overall appearance of the vegetation, including color, vigor, and growth patterns. Plant appearance can be used as an indicator of plant stress due to environmental conditions such as nutrient or water limitations. A high proportion of dead or dying vegetation indicates that recruitment is not occurring and that the site is at risk of being overtaken by undesirable plants, such as weedy annuals and invasive species (USDA NRCS, 1997). In the assessment developed for this study, sites at which the vegetative community exhibited vigorous growth and a balanced mixture of young and mature plants were given an "Excellent" score. Sites at which the majority of the plants appeared stressed, were developing close to the ground, or were dead or dying were given a "Poor" classification.

### 2.1.2. Soil erosion indicators

Since the goal of most stormwater systems is to provide some degree of water quality improvement, the loss of soil from the system by erosion- and subsequent addition of soil to stormwater leaving the system- is typically not desirable. Soil erosion indicators have been incorporated into other assessments of terrestrial ecosystem health (Manske, 2002; Romig et al., 1996) and were also included in the rubric developed for this study. To assess the prevalence of erosional activity in the system, erosional indicators including sheet and rill erosion, gully formation, plant pedestals and terracettes, and excessive deposition were considered.

Soil loss by sheet or rill erosion is evidenced by the presence of linear streamlets cut by flowing water. The frequency and spatial distribution of these streamlets was used as an indicator to assess erosion at the site. An "Excellent" rating was given to sites with no evidence of soil removal or rill formation by either wind or water. A "Poor" rating was assigned to sites at which rills were widely distributed across the area and accompanied by evidence of soil transport off the site (i.e. soil deposits within the system outlet).

It is not unlikely for some rill erosion to occur during the first growing season of a vegetated stormwater system. If the streamlets formed by sheet and rill erosion are not stabilized through revegetation, continued erosion may transform these small channels into gullies. Sites at which gullies were present and actively eroding were given a "Poor" rating. If recent gully formation was not evi-

**Table 1**
Ecological health rubric developed to assess health of ecologically designed stormwater systems.

| | 4 – Excellent | 3 – Good | 2 – Fair | 1 – Poor | Total |
|---|---|---|---|---|---|
| Plant health | | | | | |
| Density | Plants closely spaced with even distribution pattern. Less than 20% soil surface exposed. | Plants closely spaced with somewhat even distribution pattern. 20-40% soil surface exposed. | Patchy plant spacing and distribution pattern. 40-60% soil surface exposed. | Fragmented/clumped plant spacing and distribution pattern. Over 60% soil surface exposed. | |
| Diversity/Composition | Diverse plant community with no invasive species. | Diverse plant community with a few less desirable species. | Reduced diversity with some less desirable and invasive species. | Restricted diversity with many undesirable or invasive species. | |
| Vigor | Plants are vigorous with balanced mix of young and mature growth. | Plants are vigorous with no deformed growth patterns | Plants pale green or yellowing, deformed growth patterns or are developing close to the ground. | Plants appear stressed, are developing close to the ground. Most are dead or dying. | |
| Comments: (record presence of desirable and/or invasive species and whether appropriate to ecoregion and stormwater system goals.) | | | | | |
| Soil erosion indicators | | | | | |
| Sheet & Rill | Soil removal by wind or water is not evident | Small rills developing. Transported soil remains on site. | Sheet and/or rill erosion occurring in small areas. Most soil remains on site. | Sheet and rill erosion occurring in large areas. Much of the soil transported off site. | |
| Gullies | No bare soil deposits. Plants have colonized soil deposits. | A few bare soil deposits. Plants are stabilizing recent deposits. | Several small soil deposits due to deposition. Plants have not stabilized. | Deposited soil inhibiting plant growth or present as large, bare deposits. | |
| Deposition | Recent gully formation is not evident. If gullies are present, they are small and vegetated. | Very little recent gully formation. If some gullies present, they are small and vegetated. | Some recent gully formation but still small and unbranched. | Well-developed, active gullies present. | |
| Pedestaling | Plant pedestaling is not evident. | Very little plant pedestaling. | Plant pedestaling is evident but not so severe that roots are exposed. | Plant pedestaling has exposed plant roots. | |
| Comments: | | | | | |
| Soil health/structure | | | | | |
| OM Color | Topsoil clearly defined, darker than subsoil | Topsoil somewhat darker than subsoil | Topsoil only slightly darker than subsoil | No difference between color of topsoil and subsoil | |
| Roots/Residue | Roots penetrate over 15 cm deep; surface residue abundant | Roots 10 cm to 15 cm deep; surface residue abundant | Roots 5 cm to 10 cm deep; some surface residue | Roots less than 5 cm deep; no or little surface residue | |
| Subsurface compaction | Wire flag easily inserted 20 cm or more | Wire flag inserted 20 cm deep or more, but with some effort | Considerable effort required to insert flag up to 20 cm | Wire cannot be inserted to 20 cm depth without bending or breaking | |
| Soil Tilth | Soil crumbles well and is easy to slice through | Soil crumbles fairly well but some clods persist | Soil is cloddy | Soil very cloddy; clods hard like brick | |
| Comments: (Structure assessment can be performed while excavating area for earthworm count or with a soil bulk density corer.) | | | | | |
| Faunal Health | | | | | |
| Desirable species | | | | | |
| Earthworms | 10 or more earthworms in excavated area with many casts and holes | 5–9 earthworms in excavated area with some casts and holes | 1–4 earthworms in excavated area with few casts and holes | Neither earthworms or their casts and holes in excavated area | |
| Soil macrofauna | Several other species of soil macrofauna (i.e., beetle and cicadae larvae, millipedes, etc.) present | A few other species of soil macrofauna present | 1 other species of soil macrofauna present | No other species of soil macrofauna present | |
| Others (birds, dragonflies, butterflies, etc.) | Several different organisms present in/around the system | Several different organisms present in/around the system | One species of organism present in/around the system | No organisms present in/around the system | |
| Undesirable Species (mosquitoes) | No mosquitoes or mosquito larvae present | No mosquito larvae, though a few mosquitoes | Mosquito larvae present in standing water | Both mosquitoes and mosquito larvae prevalent | |
| Comments/record organisms observed here: | | | | | |

dent and previous erosional areas showed signs of stabilization with growth of vegetation, an "Excellent" rating was assigned.

Plant pedestals and scouring can be used as additional indicators of soil erosion (Pyke et al., 2002) and were also included in the rubric. Plant pedestalling occurs when soil is removed from around the base of plants via erosion and can be observed by checking for exposed roots (Manske, 2002). Scour around and beneath rocks or other hard surfaces, including the inlet and outlet pipes of stormwater systems, is another indicator of soil loss and excessive erosional energy. If neither pedestalling nor scour was present at the site, an "Excellent" rating was assigned. Sites at which plant roots were exposed and/or severe scouring had occurred received a rating of "Poor."

In keeping with the goal of water quality improvement, deposition is expected in ecologically designed stormwater systems as stormwater flows are slowed and sedimentation occurs. However, excessive deposition can have negative effects on the system by decreasing capacity or clogging of pores by fine sediments. These potential negative impacts are countered by the establishment of vegetation on soil deposits as root development and associated biological activity will improve porosity and the overall structure of deposits. To assess the impact of deposition on the health of the system, the presence and extent of soil deposits were observed. Sites in which soil deposits were being revegetated were given an “Excellent” rating. If deposited soil appeared to be inhibiting plant growth or occurred in large, bare deposits, a “Poor” rating was assigned.

### 2.1.3. Soil health/structure

Soil health indicators included in the assessment rubric were the organic matter layer, the density of roots and residue, the presence of compacted soil layers, and soil tilth. Unlike the indicators for plant health, which could be determined from the surface, the indicators for soil health require a look below the ground. Other qualitative assessments of soil health have employed either a shovel (Manske, 2002) or soil core (Arshad et al., 1996) to observe soil health indicators. In this study, a both tools were used to observe soil characteristics. The methods used to score each of the aforementioned soil health indicators, along with the reasoning behind their inclusion in the assessment developed for this study, follows.

A well-developed organic layer is beneficial for soils in stormwater management systems as this nutrient rich layer provides nutrients to support the growth of vegetation at the site while helping to improve infiltration properties of the soil (Holman-Dodds, 2006). Soils rich in organic matter tend to be darker in color than the subsoil beneath, and the relative color of the upper soil layer has been used as a simple qualitative indicator of healthy soil (Manske, 2002). The rubric developed for this study incorporated a measure of organic matter by comparing the color of the topsoil with that of the subsoil. A standard soil bulk-density core was used to remove soil from the upper 8 cm of the profile to examine the coloration of the topsoil and subsurface layers. Soils in which the topsoil was clearly darker than the subsoil were given an “Excellent” rating. If topsoil was light in color and could not be differentiated from the subsoil, a rating of “Poor” was assigned.

The abundance of roots and residue are also important components of a healthy soil ecosystem. The degree of root development will vary depending on vegetation age and type, soil conditions, and climate. For stormwater management, deep, well-developed root systems are desirable as they have a greater impact on infiltration and stormwater volume than do shallow rooted grasses (Perrygo et al., 2001; Weaver and Rowland, 1952). This is partly due to the effect of roots on soil physical properties. Over time, root penetration has been found to contribute to increased soil porosity and the development of stable soil aggregates, both of which promote higher infiltration rates (Holman-Dodds, 2006). Roots continue to enhance soil infiltration properties as they decay by increasing the organic matter content and creating macropores through which high infiltration rates have been observed due to preferential flow (Linden et al., 1991). The other advantage of deeply rooted plants over those with shallow root systems is that deeply rooted plants are able to consume water from a greater portion of the soil profile for transpiration in between storms, thus increasing the storage capacity of the soil for the next runoff event (Holman-Dodds, 2006). Rooting depth and density were observed using a shovel to expose the top 15–20 cm of soil. Although the root systems of many tallgrass prairie species can grow to depths greater than 1.5 m, root development and water usage for the tallgrass prairie was found to be concentrated in the top 15–30 cm (Knapp et al., 2001). Thus, sites at which roots penetrated 15 cm or more were given an “Excellent” rating. A dense root system at this depth would still impact infiltration for a typical rain event in the Midwest, and the required sampling depth of 15–20 cm makes observation of this indicator more practical for the intended user of this assessment. A “Poor” rating was given to sites at which roots were sparsely distributed or did not penetrate beyond 5 cm.

Root development can be adversely impacted by the presence of compacted soil layers. Subsurface compaction can also restrict infiltration and nutrient cycling processes (USDA NRCS, 1997) and is therefore undesirable in ecological stormwater systems. Compacted soil layers can be detected through the use of a penetrometer or, more simply, by probing the soil with a sharp rod or shovel (USDA NRCS, 1997). To check for the presence of compacted layers in this study, the ease with which a wire flag could be inserted was used as suggested by Romig et al. (1996). An “Excellent” rating was assigned to soils in which the flag is easily inserted to a depth of 15 cm (6 in.) or more, while a “Poor” rating was given to soils in which the flag cannot be inserted to this depth without considerable bending or breaking. The 15 cm depth was selected as a threshold for determining the presence of compacted layers based on literature reports that cite compaction layers typically occur in the upper 15 cm of the soil profile (Pyke et al., 2002; USDA NRCS, 1997).

Soil tilth is a qualitative indicator commonly used in agronomic applications to describe the soil’s suitability for supporting plant and root growth. Good tilth pertains to soils which are friable with a stable assemblage of aggregates, and is a function of soil texture, soil structure, and organic matter content (Hillel, 1998). The pore spacing in soils with good tilth is large enough to allow adequate air and water movement through the soil. Soil tilth can be assessed by crumbling a fistful of soil in one’s hand and observing the ease with which the soil crumbles and the size of the aggregates, or soil crumbs, into which the soil breaks (Manske, 2002).

### 2.1.4. Faunal health

Although largely ignored in stormwater management literature, the ecological literature focuses heavily upon the interaction between biota and the physical and chemical components of the ecosystem, including infiltration and nutrient cycling. In the soil, earthworms are among the most important components of the soil biota due to their role in the formation and maintenance of soil structure and fertility (Edwards, 2004). As earthworms burrow through soil, they ingest mineral particles, which are then mixed with organic matter in the earthworm gut and form stable aggregates when excreted. The soil aggregates formed during passage through the earthworm gut contribute to improved drainage and moisture-holding capacity of the soil profile (Edwards, 2004). Of particular interest to stormwater management is the affect of earthworms on infiltration. Earthworms are a major source of biological macropores in many soils, including those in the Midwest, and thus impact the rate at which water is transmitted through the soil profile (Linden et al., 1991). Studies that have quantified infiltration due to earthworm burrows have reported a wide range of infiltration rates, but all conclude that the flow rate in burrows is much greater than in the surrounding soil matrix (Edwards, 2004; Shipitalo and Butt, 1999; Weiler and Naef, 2003). In addition to their influence on soil properties and processes, earthworms also respond to ecosystem disturbances, such as urbanization. For example, in a study of different-aged urban systems, Smetak et al. (2007) observed significantly fewer earthworms in urban yards less than 10 years old (26 worms per square meter) than in urban yards greater than 75 years old (121 worms per square meter). Earthworm population densities of 300 per square meter have been reported for the Konza Prairie, a native tallgrass prairie reserve in northeastern Kansas (Ransom et al., 1998). Coupled with the relative ease of observing earthworms over other soil organisms, these important soil macroinvertebrates have been identified as excellent biological indicators of soil health and therefore were included in the health assessment developed for this study. The sampling method chosen to quantify earthworms depends on the basic life histories of the earthworms found in the study area (Blair et al., 1996). Earthworms are classified into one of three groups based upon their feeding and burrowing strategies: (1) epigeic species, which live in or near the surface litter, (2) endogeic species, which live within the soil profile in temporary, horizontally oriented burrow systems that are filled with cast material as the earthworm moves through the soil, and (3) anecic species, which create permanent, vertically oriented burrow systems extending up to 2 m into the soil profile. Since both shallow and deeper dwelling earthworms have been reported in the tallgrass prairie ecoregion (Ransom, et al., 1998), a combination of sampling procedures was chosen according to sampling methods outlined in the literature (Blair et al., 1996). First, vegetation and residue at the surface was cleared from an approximately 50 cm square area (2.7 ft2) and examined for surface-dwelling earthworms. A shovel was then used to excavate the area to a depth of 20 cm. All excavated soil was hand sorted to determine the presence of earthworms living in the upper region of the soil profile. A solution containing 5 g/L of dry mustard dissolved in tap water was then applied to the bottom of the excavated area to elicit any deeper-dwelling anecic earthworms present in the excavation area from their burrows to the surface. Earthworms were sampled a total of three times at each site: once in late spring and twice in the fall. These sampling times were chosen to correspond with the seasonal height of earthworm activity (Blair et al., 1996). Due to the relative invasiveness of the excavation method, only one excavation was made at the site per sampling event. Sites at which 10 or more earthworms were found were given an "Excellent" rating. If neither earthworms nor their casts or burrows were found in the excavated area, a "Poor" rating was assigned.

In addition to earthworms, other species of macrofauna inhabit the soil and contribute to biological diversity. Beetle and cicadae larvae, millipedes, and centipedes are among the most common arthropods present in prairie ecosystems (Ransom, et al., 1998) and their presence or absence was included in the rubric developed for this study. Soils in which four or more other species of soil macrofauna were found received an "Excellent" rating while soils devoid of soil macrofauna received a "Poor" rating.

Above-ground species diversity was also considered in the rubric. While not directly vital to the performance of the stormwater system, insects such as bees and butterflies can aid in pollinating wildflowers planted for aesthetic value in the stormwater system. Other insects, such as beetles, grasshoppers, and crickets attract birds to make ecological stormwater systems more of a public amenity. Sites at which several different species of insects, birds, or other wildlife were observed were given an "Excellent" rating while sites at which no organisms were observed were assigned a "Poor" rating.

While species diversity was used as an indicator of system health, some organisms are not desirable in ecologically designed stormwater systems. Mosquitoes are perhaps the foremost of these, primarily for reasons concerning public health and relations. Systems in which no adult mosquitoes or their larvae were observed were given an "Excellent" rating, while a "Poor" rating was assigned to sites at which both mosquitoes and mosquito larvae were prevalent.

### 2.2. Application of assessment rubric

Two study sites at different stages of vegetative maturity were selected for testing the ecological assessment tool. Both were located in Northeastern Kansas, a region once dominated by the tallgrass prairie ecosystem. The first of these sites was a stormwater detention basin located in a medium-density residential neighborhood in Topeka, Kansas. The basin, which will be referred to as the Quinton Heights basin after the neighborhood in which it was built, was constructed in 2004 to relieve flooding in the area. The 1550-m$^2$ basin was designed to receive runoff from a 6000-m$^2$ area, the majority of which flows down a street and into the basin through a grated opening placed in the middle of the street (Spaar, 2004). After excavation, the basin was replanted with grasses native to the tallgrass prairie, including big bluestem (*Andropogon gerardii*), Indiangrass (*Sorghastrum nutans*), switchgrass (*Panicum virgatum*), prairie cord grass (*Spartina pectinata*), and sideoats grama (*Bouteloua curtipendula*). At the time of the study, the Quinton Heights basin was in its third year of growth, so the grasses were well-developed and approaching vegetative maturity as defined by Weaver and Zink (1946). The second site, located in Johnson County, Kansas, was a prairie restoration project intended to intercept runoff from an adjacent municipal building. The 1180-m$^2$ area surrounding the building was originally a traditional fescue lawn. The lawn was sprayed with Roundup® in the spring of 2007 and a mix of mid-height prairie grasses, including sideoats grama and hairy grama (*Bouteloua hirsute*), was seeded directly into the lawn in June 2007. To help prevent erosion, a cover crop of annual rye (*Lolium multiflorum*) was planted after the native grass was seeded. Soil samples were taken from both sites and analyzed by the Kansas State University Soil Testing Lab. Both sites were classified as silty clay loams, the expected saturated hydraulic conductivity of which is 0.15 cm/h (Rawls et al., 1982).

## 3. Results and discussion

The scores for each category at both stormwater sites are summarized in Table 2. The Total column in the table represents the sum of the health scores from each of the four categories and is used as an indicator of the overall ecological health of each system. In general, the overall health score increased throughout the growing season at both sites. This was expected because many of the indicators used in the rubric, particularly vegetation density and vigor, improve as the growing season progresses. Numerically, overall scores at Quinton Heights were higher than those at Johnson County. However, the Student's *t*-test conducted between the overall health scores at the two sites indicated that differences in scores at the two sites were not statistically significant ($p = 0.71$). To understand why significantly higher scores were not observed at the more mature Quinton Heights site, a brief discussion of scores for each category follows.

### 3.1. Plant health

As expected, plant health scores were significantly higher at the Quinton Heights site than at Johnson County (Table 3, $p = 0.047$) because the Quinton Heights site was in its third growing season at the time of the study, whereas the grasses at Johnson County were seeded at the start of the study period. Differences in the vegetative maturity of the sites were most apparent in the density and types of plants that dominated either site. The grasses at the Quinton Heights site covered approximately 80% of the ground surface from the start of the growing season, whereas the emerging vegetation remained sparsely distributed for the first two months at the Johnson County site. Perennial prairie grasses, along with a mix of forbs and wildflowers, dominated the flora community at the Quinton Heights basin. Although the vegetation at the Johnson County site was healthy in appearance and covered approximately 80% of the soil surface by early August (both of which earned the site "Excellent" scores in the plant health category) the plant community was dominated by weedy annuals, including yellow foxtail (*Setaria lutescens*), stinkgrass (*Eragrostis cilianensis*), and crabgrass

**Table 2**
Summary of scores from ecological health assessment conducted at Johnson County (planted in June 2007) and Quinton Heights (planted in summer of 2004).

| Ecological health assessment | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Johnson County, KS | | | | | | Quinton Heights Topeka, KS | | | | |
| | Plant health | Soil erosion | Soil health | Fauna | Overall | | Plant health | Soil erosion | Soil health | Fauna[a] | Overall |
| 06/26/07 | 6.0 | 15.0 | 10.0 | 7.0[a] | 38.0 | 05/08/07 | 10.0 | 11.0 | - | 5.0 | 26.0 |
| 07/10/07 | 8.0 | 15.0 | 9.0 | 9.0 | 41.0 | 05/31/07 | 11.0 | 14.0 | 13.0 | 8.0 | 46.0 |
| 08/06/07 | 9.0 | 16.0 | 9.0 | 9.0 | 43.0 | 06/22/07 | 9.0 | 14.0 | 13.0 | 9.0[a] | 45.0 |
| 08/24/07 | 10.0 | 16.0 | 7.0 | 11.0 | 44.0 | 07/20/07 | 10.0 | 15.0 | 13.0 | 9.0 | 47.0 |
| 09/05/07 | 9.0 | 16.0 | 7.0 | 10.0 | 42.0 | 08/07/07 | 11.0 | 16.0 | 14.0 | 11.0 | 52.0 |
| 09/28/07 | 10.0 | 16.0 | 10.0 | 9.0[a] | 45.0 | 09/07/07 | 11.0 | 16.0 | 14.0 | 10.0 | 51.0 |
| 10/10/07 | 10.0 | 16.0 | 11.0 | 15.0[a] | 52.0 | 10/02/07 | 10.0 | 13.0 | 14.0 | 11.0[a] | 48.0 |
| Average | 8.9 | 15.7 | 9.0 | 10.0 | 43.6 | Average | 10.3 | 14.1 | 13.5 | 9.0 | 45.0 |
| Std. Dev. | 1.5 | 0.5 | 1.5 | 2.5 | 4.4 | Std. Dev. | 0.8 | 1.8 | 0.5 | 2.1 | 8.8 |
| CV (%) | 16.5 | 3.1 | 17.0 | 25.2 | 10.0 | CV | 7.3 | 12.5 | 4.1 | 23.1 | 19.5 |

[a] Earthworms counted.

**Table 3**
Plant health assessment for Johnson County and Quinton Heights, Kansas stormwater management sites.

| Plant health | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Johnson County, KS | | | | | Quinton Heights Topeka, KS | | | |
| | Density | Diversity | Vigor | Total | | Density | Diversity | Vigor | Total |
| 06/26/07 | 1 | 2 | 3 | 6 | 05/08/07 | 4 | 3 | 3 | 10 |
| 07/10/07 | 2 | 2 | 4 | 8 | 05/31/07 | 4 | 3 | 4 | 11 |
| 08/06/07 | 3 | 2 | 4 | 9 | 06/22/07 | 3 | 3 | 3 | 9 |
| 08/24/07 | 4 | 2 | 4 | 10 | 07/20/07 | 3 | 4 | 3 | 10 |
| 09/05/07 | 3 | 2 | 4 | 9 | 08/07/07 | 4 | 3 | 4 | 11 |
| 09/28/07 | 4 | 2 | 4 | 10 | 09/07/07 | 4 | 3 | 4 | 11 |
| 10/10/07 | 4 | 2 | 4 | 10 | 10/02/07 | 4 | 4 | 2 | 10 |
| Average | 3.0 | 2.0 | 3.9 | 8.9 | Average | 3.7 | 3.3 | 3.3 | 10.3 |
| Std. Dev. | 1.2 | 0.0 | 0.4 | 1.5 | Std. Dev. | 0.5 | 0.5 | 0.8 | 0.8 |
| CV (%) | 38.5 | 0.0 | 9.8 | 16.5 | CV(%) | 13.1 | 14.9 | 23.0 | 7.3 |

(*Digitaria sanguinalis*). Dominance by such less desirable plants is, however, expected in the early stages of prairie restoration projects, and the site at Johnson County was no exception. It is expected that perennial prairie grasses originally planted at the site, namely sideoats and hairy grama will establish over the next one to two years to move the site closer to its ecological potential.

Although the vegetation at the Quinton Heights site matched the desired conditions set forth by the rubric, the health of the grass community at the site may have been compromised by overmowing. The basin was mowed once in early June and again in early October, presumably as part of the city's management regime for their stormwater basins. While periodic, well-timed mowing can be used as an alternative to burning to maintain a healthy grass community (Diboll, 1984), inappropriate timing and frequency of mowing may adversely affect the health of tallgrass prairie species. Studies of grasslands and restored prairies suggest mowing once on an annual or semi-annual basis either in early spring or at the end of the growing season (Dale, 1982; Diboll, 1984). In addition to the less than desirable timing and inappropriate frequency of mowing in the basin, both mowings left a considerable thatch layer in the basin. While a moderate mulch covering is desirable to promote infiltration, maintain plant-water relations, and help prevent erosion, excessive mulch has been found to retard emergence of regrowth, reduce the amount of biomass produced throughout the growing season, and reduce plant diversity (Weaver and Rowland, 1952). The mowing in early October was potentially damaging to the development of the grass below the ground as well; since temperatures were still warm enough to support above-ground biomass growth, the grasses may have pulled reserves from the roots to support recovery growth aboveground, thus weakening the root system (Knapp et al., 2001). Due to the potentially negative impacts of over-mowing on the growth of tallgrass species, mowing treatments are recommended either in the spring or late fall after the first killing frost (Schacht et al., 1996).

### 3.2. Soil erosion indicators

Scores for soil erosion remained fairly constant at each site throughout the observation period and, although numerically higher at the Johnson County site, were not found to be statistically different (Table 4, $p = 0.058$). The Johnson County site maintained scores in the "Excellent" range, a result which can be attributed to the site's relatively flat topography and small watershed. Erosive and depositional forces were more prevalent at the Quinton Heights site where small gullies formed along the steep sides of the basin and incoming stormwater flows from the streets provided an abundant supply of sediment and debris to the basin. The erosional and depositional features of the Quinton Heights basin did not, however, present a great concern to the stability of the site as the grasses in the basin were revegetating the gullies and sediment deposits. Accordingly, the relationship between soil erosion indicators and vegetation health is evidenced by the increase in soil erosion scores throughout the growing period at Quinton Heights, despite heavy rainfall events that also occurred during this period. The drop in the erosional indicator score for the October observation at Quinton Heights is related to the late-season mowing of the basin, which removed vegetation along gullies and the sides of the basin, thus leaving the basin more susceptible to erosion.

### 3.3. Soil health and structure

Soil health and structure scores were significantly higher at the Quinton Heights site (Table 5, $p = 8.65 \times 10{-}5$). Higher scores at Quinton Heights are attributed to the more mature vegetative

**Table 4**
Soil Erosion assessment for Johnson County and Quinton Heights, Kansas stormwater management sites.

| Soil erosion | Johnson County, KS | | | | | | Quniton Heights Topeka, KS | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sheet/Rill | Deposition | Gullies | Pedestaling | Total | | Sheet/Rill | Deposition | Gullies | Pedestaling | Total |
| 06/26/07 | 3 | 4 | 4 | 4 | 15 | 05/08/07 | 4 | 2 | 2 | 3 | 11 |
| 07/10/07 | 3 | 4 | 4 | 4 | 15 | 05/31/07 | 4 | 3 | 3 | 4 | 14 |
| 08/06/07 | 4 | 4 | 4 | 4 | 16 | 06/22/07 | 4 | 3 | 3 | 4 | 14 |
| 08/24/07 | 4 | 4 | 4 | 4 | 16 | 07/20/07 | 4 | 4 | 3 | 4 | 15 |
| 09/05/07 | 4 | 4 | 4 | 4 | 16 | 08/07/07 | 4 | 4 | 4 | 4 | 16 |
| 09/28/07 | 4 | 4 | 4 | 4 | 16 | 09/07/07 | 4 | 4 | 4 | 4 | 16 |
| 10/10/07 | 4 | 4 | 4 | 4 | 16 | 10/02/07 | 4 | 3 | 2 | 4 | 13 |
| Average | 3.7 | 4.0 | 4.0 | 4.0 | 15.7 | Average | 4.0 | 3.3 | 3.0 | 3.9 | 14.1 |
| Std. Dev. | 0.5 | 0.0 | 0.0 | 0.0 | 0.5 | Std. Dev. | 0.0 | 0.8 | 0.8 | 0.4 | 1.8 |
| CV (%) | 13.1 | 0.0 | 0.0 | 0.0 | 3.1 | CV (%) | 0.0 | 23.0 | 27.2 | 9.8 | 12.5 |

**Table 5**
Soil Health assessment for Johnson County and Quinton Heights, Kansas stormwater management sites.

| Soil health | Johnson County, KS | | | | | | Quniton Heights Topeka, KS | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | OM Color | Roots | Compaction | Tilth | Total | | OM Color | Roots | Compaction | Tilth | Total |
| 06/26/07 | 3 | 1 | 3 | 3 | 10 | 05/08/07 | – | – | – | – | – |
| 07/10/07 | 3 | 1 | 3 | 2 | 9 | 05/31/07 | 4 | 3 | 3 | 3 | 13 |
| 08/06/07 | 3 | 2 | 2 | 2 | 9 | 06/22/07 | 4 | 3 | 3 | 3 | 13 |
| 08/24/07 | 1 | 2 | 2 | 2 | 7 | 07/20/07 | 4 | 3 | 3 | 3 | 13 |
| 09/05/07 | 1 | 2 | 2 | 2 | 7 | 08/07/07 | 4 | 3 | 3 | 4 | 14 |
| 09/28/07 | 3 | 2 | 3 | 2 | 10 | 09/07/07 | 4 | 3 | 3 | 4 | 14 |
| 10/10/07 | 4 | 2 | 3 | 2 | 11 | 10/02/07 | 4 | 3 | 3 | 4 | 14 |
| Average | 2.6 | 1.7 | 2.6 | 2.1 | 9.0 | Average | 4.0 | 3.0 | 3.0 | 3.5 | 13.5 |
| Std. Dev. | 1.1 | 0.5 | 0.5 | 0.4 | 1.5 | Std. Dev. | 0.0 | 0.0 | 0.0 | 0.5 | 0.5 |
| CV (%) | 44.1 | 28.5 | 20.8 | 17.6 | 17.0 | CV (%) | 0.0 | 0.0 | 0.0 | 15.6 | 4.1 |

community, the root development and organic inputs of which contributed to a deeper organic layer and granular structure of the soil. In general, soil health and structure scores remained fairly constant throughout the observation period, particularly at the Quinton Heights site (coefficient of variation = 4.1%). The observed stability in scores was anticipated since the majority of the indicators upon which the soil health score was based- namely the depth of the organic matter layer, soil compaction, and tilth- are related to the structure of the soil and would not be expected to change significantly over a single growing season (Vogel and Roth, 2001). Greater variability was observed in the scores at the Johnson County site (coefficient of variation = 17%). The spatial variability of soil properties across the Johnson County site, particularly with regards to the organic matter layer, is attributed to recent soil disturbance during planting and less uniform rooting depth and density. An additional source of variability was the soil moisture at the time the assessment was completed. The soil moisture was found to affect the ease with which a wire flag, used to determine the presence of compacted soil layers, could be inserted into the soil so that drier soils appear to be more compacted. Skewed compaction scores due to soil moisture content could be avoided by conducting the health assessment when the soil moisture is about the same, for instance, 48 h after rainfall. Other physical features could also be incorporated into the rubric to confirm the presence of suspected soil compaction, including blocky, dense soil structure over less dense soil layers or horizontal root growth (USDA NRCS, 1997). Another adjustment that could be made to the soil health portion of the assessment would be to measure the depth of the granular, organic matter rich layer in the uppermost region of the soil profile rather than simply compare the color of the topsoil to that of the subsoil. Although it was not part of the assessment developed for this study, the depth of this layer was observed at both sites. At Johnson County, only the upper 1–3 cm of the soil profile exhibited a granular organic layer as compared to the top 6 cm at Quinton Heights. Differences in the development of this layer are most likely related to the depth and activity of the roots of the grasses at each of the sites and their impact on soil structure. A quantified measure such as this would provide a better indication of changes in the organic content and structure of the soil over time than the more subjective color-comparison method.

### 3.4. Faunal health

Of the four categories used to assess the ecological health of the study sites, the scores for the faunal health category were the most variable over time. This result could also be expected since the biological indicators upon which scores were based are mobile, and, unlike the grasses or soils in the system, may or may not be present at the time and location at which the assessment was conducted (Table 6). Due to the variable nature of the faunal health scores at each site, the Student's $t$-test returned no significant differences in scores between the two ($p = 0.35$). Both sites hosted a variety of birds and insects and received scores of "Good" to "Excellent" during each assessment. Earthworms were found at the Johnson County site in each of the three earthworm sampling trials, but none were observed at the Quinton Heights site. The earthworms recovered at the Johnson County site were predominantly epigeic and endogeic species and resided near the soil surface. Because the earthworm species encountered at the site were found near the surface, the earthworm sampling procedure was adjusted to more effectively account for the earthworms present in the sampling area. During the sampling trials, it was found that more worms could be found when the sampling area was cleared of vegetation and the dry mustard solution was applied directly to the soil surface prior to excavation. After sufficient time was allowed for shallow-dwelling earthworms to navigate to the surface, the area

**Table 6**
Fauna assessment for Johnson County and Quinton Heights, Kansas stormwater management sites.

| Fauna | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Johnson County, KS | | | | | | Quniton Heights Topeka, KS | | | | |
| | Worms | Soil fauna | Others | Mosquitoes | Total | | Worms | Soil fauna | Others | Mosquitoes | Total |
| 06/26/07 | 1 | 1 | 1 | 4 | 7 | 05/08/07 | 1 | 1 | 1 | 2 | 5 |
| 07/10/07 | 2 | 1 | 3 | 3 | 9 | 05/31/07 | 1 | 1 | 4 | 2 | 8 |
| 08/06/07 | 1 | 1 | 3 | 4 | 9 | 06/22/07 | 1 | 1 | 3 | 4 | 9 |
| 08/24/07 | 2 | 2 | 3 | 4 | 11 | 07/20/07 | 1 | 1 | 3 | 4 | 9 |
| 09/05/07 | 1 | 1 | 4 | 4 | 10 | 08/07/07 | 1 | 2 | 4 | 4 | 11 |
| 09/28/07 | 1 | 1 | 3 | 4 | 9 | 09/07/07 | 1 | 1 | 4 | 4 | 10 |
| 10/10/07 | 3 | 4 | 4 | 4 | 15 | 10/02/07 | 1 | 3 | 4 | 3 | 11 |
| Average | 1.6 | 1.6 | 3.0 | 3.9 | 10.0 | Average | 1.0 | 1.4 | 3.3 | 3.3 | 9.0 |
| Std. Dev. | 0.8 | 1.1 | 1.0 | 0.4 | 2.5 | Std. Dev. | 0.0 | 0.8 | 1.1 | 1.0 | 2.1 |
| CV (%) | 50.1 | 72.2 | 33.3 | 9.8 | 25.2 | CV (%) | 0.0 | 55.1 | 33.9 | 28.9 | 23.1 |

was excavated to the 20-cm depth, hand-sorted, and the dry mustard solution was then applied to the bottom of the excavated area. Earthworm densities at the Johnson County site ranged from 15 to 25 individuals per square meter, which is in line with values reported in the literature for recently developed urban lawns (Smetak et al., 2007). The absence of earthworms from the sampling trials at the Quinton Heights sites does not preclude the presence of earthworms in the basin. It does, however, suggest that a migrational barrier or other condition may exist to hinder the establishment of a substantial earthworm population in the basin.

The faunal health category also accounted for the presence of nondesirable species. The primary organism of concern in stormwater systems is the mosquito. Throughout the study period, only one mosquito was observed at the Johnson County site. At the Quinton Heights site, mosquito larvae were regularly observed in a small depression at the center of the basin in which water remained standing after rainfall and provided a place for the larvae to grow. Mosquito larvae were also occasionally present in water samples taken at the outlet of the system. Despite the presence of mosquito larvae at the site, adult mosquitoes were never observed, even during lengthy visits to the basin to conduct infiltration tests. Full development of the larvae to adult mosquitoes was probably somewhat controlled by the drying out of the depression before larvae emerged or by washout of the larvae during storms.

## 4. Conclusions

One of the challenges to successfully implementing ecologically engineered stormwater systems is continued maintenance and monitoring after installation. The parties typically responsible for monitoring, usually a municipal stormwater or public works department, lack sufficient time and funding to conduct detailed chemical and hydraulic analyses. The objective of this study was to develop and assess the applicability of an ecological health rubric to rapidly assess the overall health of eco-based stormwater systems. The health assessment developed in this study was applied to two urban stormwater sites planted with native prairie grasses. One of the sites, Quinton Heights, was in its third season of operation and approaching vegetative maturity. The second site, Johnson County, had just been converted from a traditional turf lawn to prairie grasses at the start of the study period. Although the scores for the overall ecosystem health were generally higher at the more mature Quinton Heights site, differences between the two sites were not found to be statistically significant. However, statistically significant differences in the scores between the two sites were observed for the plant health, soil erosion, and soil health and structure categories. The most evident difference between the two sites was in the soil health and structure category. The significantly higher soil health scores at the Quinton Heights site were attributed to greater root development and density, which have in turn contributed to soil tilth and structure at the site. One of the most obvious visual differences between the two sites was the vegetation composition. The vegetative community at Quinton Heights, which was composed primarily of perennial tallgrass prairie species, received higher scores than the Johnson County site, which was dominated by weedy annuals. Still, the difference between vegetation health scores were not as high as expected. Lower than anticipated vegetation health scores at the Quinton Heights site are attributed to two mowing events in which the grasses were cut very short and a thick layer of potentially growth-inhibiting grass clippings was left.

Based on experience applying the health rubric in this study, it is believed that the information collected from a qualitative assessment can provide valuable information about the condition and potential performance of a stormwater system, especially when quantitative data is not available, as well as to aid in developing proper maintenance regimes to maintain the health of the system.

The function and sustainability of ecologically designed stormwater systems depends in part on the maintenance of ecosystem processes. Maintaining a healthy ecosystem has important implications for the long-term management of ecologically designed systems. For example, in the case of the integration of a tallgrass prairie ecosystem with stormwater management, a proper burning or mowing regime should be followed to ensure the continued health of the vegetation, and thus the roots which positively impact soil infiltrative properties. If a mowing regime is adopted, care should be taken to mow either early in the growing season or at its conclusion, and to remove at least part of the grass clippings to make way for regrowth.

Although not statistically significant, the general upward trend in overall health scores at both sites throughout the study period supports the hypothesis that the ecological health of a site improves over time. These improvements are likely to be most evident over the span of years rather than a single growing season. The time to establish a healthy, functioning ecosystem also has important implications for the design of ecologically based stormwater systems. Unlike traditionally constructed systems, ecologically designed systems will not be fully functional at the time of their installation, but will have the potential to improve over the first few growing seasons.

Additional research is needed to establish a correlation between the ecological health score and the actual hydraulic and pollutant removal performance of the system. Although hydraulic and water quality data were collected at the Quinton Heights basin, the amount of data collected was not sufficient to make any firm connections between the ecological health score from the rubric developed for this study and the true functionality of the system. In order to make this ecological assessment tool more useful to the stormwater management community, the rubric will be applied over the next few growing seasons at these sites. Coupling ecological health scores with continued hydraulic and water quality monitoring data will aid in evaluating the usefulness of and ecological health assessment to rapidly assess the potential of the system to fulfill intended hydraulic and water quality functions.

## References

Arshad, M.A., Lowery, B., Grossman, B., 1996. Physical tests for monitoring soil quality. In: Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. Soil Science Society of America, Madison, WI, pp. 123–142.

Blair, J.M., Bohlen, P.J., Freckman, D.W., 1996. Soil invertebrates as indicators of soil quality. In: Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. Soil Science Society of America, Madison, WI, pp. 273–287.

Collins, S.L., Knapp, A.K., Briggs, J.M., Blair, J.M., Steinauer, E.M., 1998. Modulation of diversity by grazing and mowing in a native tallgrass prairie. Science 280, 745–747, no. 5364.

Culbertson, T.L. and Hutchinson, S.L., 2004. Assessing bioretention cell function in a midwest continental climate. 2004 ASAE Annual Meeting. Paper number 047051.

Dale Jr, E.E., 1982. The effects of mowing and burning on a restored prairie at Pea Ridge National Military Park, Benton County, Arkansas. In: Brewer, R. (Ed.), Proc. Eighth North American Prairie Conference. Western Michigan University, Kalamazoo, MI, pp. 134–138.

Debo, T., Reese, A.J., 2003. Municipal Stormwater Management, 2nd Ed. CRC Press, Boca Raton.

Diboll, N., 1984. Mowing as an alternative to spring burning for control of cool season exotic grasses in prairie grass plantings. In: Clamby, G.K., Pemble, R.H. (Eds.), The Prairie: Past, Present and Future. Proc., Ninth North American Prairie Conference. North Dakota State University, Fargo, ND, pp. 204–209.

Doran, J.W., Parkin, T.B., 1996. Quantitative indicators of soil quality: a minimum data set. In: Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. Soil Science Society of America, Madison, WI, pp. 25–37.

Edwards, C., 2004. The importance of earthworms as key representatives of the soil fauna. In: Edwards, C. (Ed.), Earthworm Ecology. CRC Press, Boca Raton, FL, pp. 3–11.

Hillel, D., 1998. Environmental Soil Physics. Academic Press, San Diego, CA.

Holman-Dodds, J.K., 2006. "Evaluation of the hydrologic benefits of infiltration-based stormwater management." Ph.D. diss. University of Iowa, Department of Civil and Environmental Engineering, Iowa City, IA.

Jørgensen, S., Costanza, R., Xu, F. (Eds.), 2005. Handbook of Ecological Indicators for Assessment of Ecosystem Health. CRC Press, Boca Raton.

Knapp, A.K., Briggs, J.M., Koelliker, J.K., 2001. Frequency and extent of water limitation to primary production in a mesic temperate grassland. Ecosystems 4, 19–28.

Linden, D.R., Trojan, M.D., Zheng, F., Allmaras, R.R., 1991. Modeling preferential flow in earthworm burrows. In: Gish, T.J., Shiromohammadi, A. (Eds.), Preferential Flow: Proc. of the National Symposium. Chicago, IL. American Society of Agricultural Eng. St. Joseph, MI USA, pp. 268–277.

Manske, L.L., 2002. Grassland Ecosystem Monitoring: A Nonquantitative Procedure for Assessing Rangeland Performance Status. North Dakota State University Dickinson Research Extension Center (February 8, 2007) http://www.ag.ndsu.nodak.edu/dickinso/research/2001/range01j.htm.

Odum, H.T., 1962. Man and ecosystem. In: Proc. Lockwood Conference on the Suburban Forest and Ecology , Bulletin Connecticut Agricultural Station.

Ohlenbusch, P.D., Bidwell, T., Fick, W.H., Kilgore, G., Scott, W., Davidson, J., Clubine, S., Mayo, S.J., Coffin, M., 2001. Sericea lespedeza: history, characteristics, and identification. Kansas State University, Retrieved Novemeber 4, 2007 from http://www.oznet.ksu.edu/library/crpsl2/mf2408.pdf.

Perrygo, C.L., Shirmohammadi, A., Ritchie, J.C., Rawls, W.J., 2001. Effect of eastern gamagrass on infiltration rate and soil physical and hydraulic properties. In: Bosch, D.D., King, K.W. (Eds.), Preferential Flow, Water Movement and Chemical Transport in the Environment, Proc. 2nd Int. Symp. ASAE 701P0006, St. Joseph, Michigan, pp. 265–268.

Pyke, D.A., Herrick, J.E., Shaver, P., Pellant, M., 2002. Rangeland health attributes and indicators for qualitative assessment. J. Range Manage. 55 (6), 584–597.

Ransom, M.D., Rice, C.W., Todd, T.C., Wehmueller, W.A., 1998. Soils and soil biota. In: Knapp, A.K., Briggs, J.M., Hartnett, D.C., Collins, S.L. (Eds.), Grassland Dynamics: Long-term Ecological Research in Tallgrass Prairie. Oxford University Press, New York, NY, pp. 48–66.

Rawls, W.J., Brakensiek, D.L., Saxton, K.E., 1982. Estimation of soil water properties. Trans. ASAE 25 (5), 1316–1320, 1328.

Romig, D.E., Garlynd, M.J., Harris, R.F., 1996. Farmer-based assessment of soil quality: a soil health scorecard. In: Doran, J.W., Jones, A.J. (Eds.), Methods for Assessing Soil Quality. Soil Science Society of America, Madison, WI, pp. 39–60.

Schacht, W.H., Stubbendieck, J., Bragg, T.B., Smart, A.G., Doran, J.W., 1996. Soil quality response of reestablished grasslands to mowing and burning. J. Range Manage. 49, 458–463.

Shipitalo, A.U., Butt, K.R., 1999. Occupancy and geometrical properties of Lumbricus terrestris l. burrows affecting infiltration. Pedobiologia 43 (6), 782–794.

Smetak, K.M., Johnson-Maynard, J.L., Lloyd, J.E., 2007. Earthworm population density and diversity in different-aged urban systems. Appl. Soil Ecol. 37, 161–168.

Spaar, D., 2004. Drainage improvement plan, Project No. 50218-00, Quinton Heights area. City of Topeka Public Works Engineering, Topeka, Ks.

USDA, NRCS. 1997. National range and pasture handbook. USDA, NRCS, Grazing Lands Technol. Inst. 190-vi-NRPH, Washington, D.C.

Vogel, H.J., Roth, K., 2001. Quantitative morphology and network representation of soil pore structure. Adv. Water Res. 24, 233–242.

Watzin, M.C., McIntosh, A.W., 1999. Aquatic ecosystems in agricultural landscapes: a review of ecological indicators and achievable ecological outcomes. J. Soil Water Conserv. 54 (4), 636.

Weaver, J.E., 1958. Classification of root systems of forbs of grassland and a consideration of their significance. Ecology 39 (3), 393–401.

Weaver, J.E., Rowland, N.W., 1952. Effects of excessive natural mulch on development, yield, and structure of native grassland. Botanical Gazette 114 (1), 1–19.

Weaver, J.E., Zink, E., 1946. Annual increase of underground materials in three range grasses. Ecology 27 (2), 115–127.

Weiler, M., Naef, F., 2003. An experimental tracer study of the role of macropores in infiltration in grassland soils. Hydrol. Process. 17, 477–493.

Please cite this article in press as: Moore, T., et al., A qualitative assessment tool for ecologically based stormwater systems. Ecol. Eng. (2011), doi:10.1016/j.ecoleng.2011.03.021