Water Environment Research Center
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Water Resources Agency, Ministry of Economic Affairs, ROC
University of Virginia, USA
National Taipei University of Technology, ROC

Journal of Ecotechnology

Vol.2 No.2 December 2006

Water Environment Research Center

Journal of Ecotechnology

Volume 2, Number 2

semi-annual

December, 2006

Content

Publisher	Tsu-Tian Lee
Circulation Dep.	Water Environment Research Center, NTUT.
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Preface

This issue marks the end of the second year of existence of the ***Journal of Ecotechnology (JET).*** The publication of the JET is pert of the research activities of the Water Environment Research Center (WERC) of the National Taipei University of Technology (NTUT). WERC was established in 1999, with major funding from the Water Resources Bureau (predecessor of the current Water Resources Agency or WRA), and collaboration from NTUT and the University of Virginia (UVA). Since its inception, WERC has made ecological engineering one of the focal points of its research and outreach, as well as international collaborative activities.

Launched in 2005, ***JET*** was designed to provide a platform for professionals to obtain and dissimilate information on ecological engineering. Presently the *Journal* contains a news brief section and a technical paper section. The eventual goal is for the *Journal* to become a full-fledged scientific journal and attain SCI recognition.

The mission of WERC, with ***JET*** as one of the implementation tools, is described in a broader sense by the American Ecological Engineering Society's (AEES) mission statement:

To promote the development of sustainable ecosystems that integrate human society with its natural environment for the benefit of both by fostering education and outreach, extending professional development and associations, raising public awareness, and encouraging original research.

In the past few years, the application of ecological engineering methods to water and environmental projects has received much attention in Taiwan. The government essentially requires all water resources engineering projects be considered for potential ecological engineering applications. Leading the way is the Water Resources Agency, which funded several large projects that included ecological engineering method applications. Similar studies have been funded by the Council of Agriculture and the Environmental Protection Administration. To promote a dialogue among local and international ecological engineering professionals, the Public Construction Commission sponsored a hugely successful major international conference on ecological engineering, organized by NTUT, in Taipei in 2004. The second such conference was just held in Taipei earlier this month.

The successful application of ecological engineering in water/environmental projects requires a close coordination between ecologists and engineers. In Taiwan, there has been increasingly more such coordination in recent years, thanks to the great efforts exercised by governmental agencies and academic groups. It is our sincere hope that the trend will continue and that the principles of ecological engineering will be considered in all engineering applications.

Shaw L. Yu
November 19, 2006
Reston, Virginia

Ecological Engineering in Taiwan

— An Assessment of Progress

Shin-Hwei Lin[1]

Taiwan has begun to promote the application of ecological engineering since 1991. Governmental agencies as well as academic groups have been aggressively developing and searching for engineering technologies that can satisfy ecological requirements. Among governmental agencies, the Soil & Water Conservation Bureau of the Council of Agriculture (COA) has implemented many ecological engineering projects, including stream habitat improvement, fish-passage design, landscaping and vegetative cover for villages, detention pond and debris flow damaged area ecological engineering design, and establishment of reference and description materials, etc. The Forest Bureau of COA has also supported R & D studies on ecological engineering methods applied to forest roads and on fish-passage and wooden structures in lumber areas.

The Water Resources Agency (WRA) of the Ministry of Economic Affairs has sponsored a substantial number of studies on the application ecological engineering methods in water resources engineering and has incorporated these methods in many water projects, such as non-traditional levee design and restoration works in flooded areas. At the Department of Transportation, the Highway Bureau has assessed the application of landscaping and ecological corridor design in road projects. The Council of Public Works has held ecological engineering fairs; international conferences on ecological engineering, and established a category of ecological engineering for its public works gold medal competition, which is designed to honor those associated with good ecological engineering applications, and to enhance the enthusiasm of participation from governmental agencies and common citizens.

In the academic arena, much information on environmental – ecological indices, biological indices, and composite environmental indices have been generated through research studies, conferences, and journal publications. This information provides a quantitative basis for comparing before and after the implementation of ecological engineering projects, which is needed in the

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evaluation of the cost-effectiveness of such projects.

There have been successes as well as failures in the application of ecological engineering methods in Taiwan. Failures usually are associated with engineering design problems, location of a project and improper construction materials. In the future, we need to assess the success and failure cases in order to find ways of improving ecological engineering applications. Regional design and specification guidelines need to be established. A set of ecological engineering design principles and implementation protocols, which differ from the traditional civil and construction guidelines and protocols, should be developed. By compiling all the information on ecological engineering applications in Taiwan and abroad, we can establish a “localized” framework for ecological engineering applications in Taiwan.

(Translated and edited by Shaw L. Yu)

台灣自 1991 年起開始推行生態工程,政府機關與學術團體積極研發與探索合乎生態需求之工程技術，在政府機關方面，行政院農業委員會水土保持局辦理多項生態工程計畫，內容包含野溪棲地改善、魚道設計、農村景觀植被、滯洪池與土石流災區生態工程設計、參考圖說資料建置等項目；行政院農業委員會林務局亦委託進林道生態工法、林班地魚道與木構造物之研發；經濟部水利署進行非規格化堤防與與易淹水地區整治技術之研發；交通部公路總局進行景觀與生態廊道設計與道路應用案例評估；行政院公共工程委員會推動生態工程博覽會、國際研討會與公共工程金質獎(首次增列生態工程類)選拔，獎勵優良生態工程之執行單位與相關人員，提高政府部門與民間參與之熱忱。學術團體方面，許多關於環境生態指標、生物指標及環境綜合指數之研究陸續進行研討會與論文之期刊發表，可提供生態工程改善前後環境品質改變之量化數據，以利工程成效評估。

生態工程之推行至今，有成功也有失敗之案例，失敗案例是工程設計問題、設置地點錯誤或是資材使用年限到期? 未來仍需要將成功與失敗實例進行探討與改進，進行不同區域環境提出制式化之規範，且對於生態工程設計監造需另建立有一套異於一般土木或傳統工程之標準作業流程，將本土化生態工程資訊整合，以擴大台灣生態工程之格局。

Ecotechnology at work－

A success story at Guandu Nature Park in Taipei

In northern Taiwan at the junction of Damchui and Jilong Rivers there is a heavenly place for migrating birds that it's called the "Guandu Nature Park". Guandu is a major stopover site for migrating birds, especially waterfowls and shorebirds, as well as an important wintering and breeding ground for many species. Two hundred twenty-nine species of birds have been recorded at Guandu so far, qualifying this wetland complex as an Important Bird Area (IBA) recognized by BirdLife International.

In 1983 the government created the "Guandu Waterbird Refuge", and the Tourism Bureau classified Guandu as a major tourist attraction. The Nature Park covers 57 hectares divided into the Main Area, Core Reserve Area, Outdoor Observational Areas, and the Sustainable Management Area, as shown in Figure 1. Figure 2 depicts an overview of the Park.

Figure 1. Park Map(http://www.gd-park.org.tw/en/e1.htm)

On December 1, 2001, administration of Guandu Nature Park was handed over to the Wild Bird Society of Taipei, a Non-Governmental Organization (NGO) with thirty years of experience in conservation and environmental education. Guandu Nature Park thus became the first protected area in Taiwan to be managed by an NGO. As a non-profit organization, the Wild Bird Society of

Taipei channels 100% of the income generated by Guandu Nature Park back into the management of the park. With this unprecedented action, the Wild Bird Society of Taipei aims to combine the resources and energy of both governmental and public interests and recreate a healthy wetland ecosystem for the purposes of both conservation and environmental education (see Figure 3).

Figure 2. Overview of Park

(http://www.gd-park.org.tw/en/e1.htm)

Figure 3. Field class for kids

(http://www.gd-park.org.tw/en/e1.htm)

Reference:

http://www.gd-park.org.tw/en/e1.htm

Educational and Public Outreach Activities

—Visit to the Fei-tsuei Reservoir Watershed

Date: Septerber/23th/2006

Destination: Fei-tsuei Reservoir and the Jr-tan Water Treatment Plant, Taipei.

Sponsored by: Water Resources Agency, Ministry of Economic Affairs

Water Environment Research Center, NTUT

Hosts: Bureau of Fei-tsuei Reservoir Administration,

Taipei City Government Taipei Water Department

Participants: Graduate students, Seniors majoring in environment, civil, hydraulic engineering, and interested citizens.

Table1. Activities schedule

Time	Activity	Location
08：00～08：30	Assemble	NTUT
10：00～10：30	Introduce Fei-tsuei Reservoir	Administration of Fei-tsuei Reservoir
10：30～11：30	Tour of dam	Fei-tsuei Reservoir
11：30～13：00	Lunch	Jr-tan Water Treatment Plant
13：30～14：00	Introduce Jr-tan Water Treatment Plant	Jr-tan Water Treatment Plant
14：00～15：00	Visit to Jr-tan Water Treatment Plant	Jr-tan Water Treatment Plant
15：00～16：00	Conclusion	NTUT

Figure 1. Educational tour to the Fei-tsuei Reservoir

Figure 2. Educational tour of the Jr-tan Water Treatment Plant

2006 International Symposium on Ecological Engineering

Date:11/9th ~10th/2006 （Thursday～Friday）

Sponsored by: Public Construction Commission, Executive Yuan

Organized by: The Ecological Engineering Research Center, National Taiwan University (NTU), Taiwan

Co-Sponsored by: Department of Bioenvironmental Systems Engineering, NTU, Taiwan

Chinese Institute of Civil and Hydraulic Engineering

Taiwan Geotechnical Society

Chinese Society of Agricultural Engineers

Genesis Group, Taiwan

Description:

The conference was the second of such meeting sponsored by the Public Construction Commission. The first one, in 2004, was organized by NTUT and was a huge success.

Reference:

The objective of the 2006 conference was to provide a forum for invited scholars and experts, who are professionals in ecological engineering and related fields, from Europe, America and Asia to report on their experiences and recent advances in ecological engineering, especially in the areas of stream restoration and road construction ecology. The exchange between experts from abroad and Taiwan will be helpful in the integration of ecological principles with engineering practices in Taiwan. The conference was very successful. The invited papers are published in a book. A Conference Proceeding CD is available.

Reference:

http://203.64.157.65/2006isee/news.asp

"Climate Change, Taiwan Cares" Festival and Parade

Mitchell Tsai[1]

On November 4, 2006 people from 45 countries simultaneously demanded action from global leaders to stop climate change. In Taiwan more than 500 people gathered together at Daan Forest Park in Taipei for the "Climate Change, Taiwan Cares" Festival and Parade (http://blog.yam.com/climatechange). The festival featured skits, musical performances, information booths, and the sale of environmentally-friendly goods. Parade participants carried umbrellas as well as dressed as bicyclists, animals, and trees promoting environmentally friendly lifestyles.

The event was held by a coalition of more than 11 Taiwanese environmental groups, including Taiwan Environmental Action Network, Society of Wilderness, Taiwan Green Party, Homemaker's Association, Green Citizen Action Alliance, Wild at Heart Legal Defense Association, and Taiwan Environmental Protection Union. The groups demanded that Taiwan implement Kyoto Protocol requirements stipulating that CO2 emissions be brought to 5% below year-1990 levels by 2012-2016. The groups also want the government to set long-term targets for CO2 emissions at 50% below 2005 levels by 2050.

Despite the island's political and diplomatic isolation, the country is increasing its participation in international climate change instruments. Taiwan Environmental Action Network recently joined Climate Action Network (http://www.climatenetwork.org), a coalition of over 365 international non-governmental organizations working collectively on climate change issue. This will give an opportunity for Taiwanese environmental groups to exchange information and work collectively with other NGOs around the world to address climate change.

[1] Taiwan Environmental Action Network-Campaign Coordinator

Bridging the Gap Between BMP Effectiveness and Receiving Water Quality Protection

T. Andrew Earles[1], Jane K. Clary[2], Rachel Pittinger[3], and David B. Mehan[4]

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Abstract

Since the early 1990s when Phase I of the National Pollutant Discharge Elimination System (NPDES) Stormwater Regulations went into effect in the United States, significant research has been conducted to evaluate the effectiveness of stormwater best management practices (BMPs). This type of research has proliferated since the adoption of Phase II NPDES Stormwater Regulations in 2003 since many smaller municipalities, unregulated under Phase I, are now required to have NPDES permits for stormwater discharges and face the challenges of selecting BMPs that are effective for management of non-point source (NPS) pollution and protection of receiving water quality.

Significant progress has been made in assessing BMP effectiveness and understanding the underlying physical, chemical and biological processes that remove or transform pollutants in stormwater. Engineers now have reasonable expectations of BMP pollutant removal and effluent water quality given a targeted parameter (often total suspended solids [TSS]), anticipated BMP loading from a defined tributary area, BMP design criteria and/or other factors; however, determining the effects of multiple BMPs on the chemistry, biology and physical characteristics of receiving waters at the development- or watershed-scale is less well documented.

This paper presents an approach to evaluating the effects of BMPs on receiving water quality by examining the expansion of the Copper Mountain Base Area in Summit County Colorado, USA.

The Copper Mountain Base Area expansion project provides an example of how careful planning, implementation and monitoring of water quality protection strategies consisting of structural and non-structural BMPs can be effective at protecting receiving waters from the effects of development. Water quality and biological monitoring data were collected before, during and after construction for West Tenmile Creek, which runs through the heart of the base area expansion project. The results demonstrated that the creek has maintained excellent water quality, habitat quality and aquatic life, and that BMPs for the Copper Mountain Base Area expansion project have been effective at protecting receiving water quality.

Keywords: NPDES; Stormwater; BMPs; TSS; Water Quality Protection

BMP 效率與水質保護關係之建立

自 1990 年代初，美國推動全國污染排放消除系統（NPDES）中有關雨水第一梯次之管制辦法以來，已經有相當多針對最佳管理措施（BMP）去污效率探討之研究。尤其從 2003 年第二梯次管制辦法實施後，因為人口十萬以上的城市皆列入管制範圍，而需要申請雨水排放許可證，並對非點源污染及 BMP 之使用必須執行，所以自 2003 年以來，全國有更多對 BMP 效率評估之研究。

目前，經由對 BMP 效率多年以來之研究成果。一般而言，對 BMP 處理雨水逕流帶來污染物之機制，如物理、化學或生物性等，已有相當之瞭解，BMP 對某些指定之污染物（通常含總懸浮固體物，TSS）的去除率，以及相關之設計準則等也有甚多的文獻報導。相對而言，對於以一集水區整體為考量，區內 BMP 之使用對水質改善之評估之文獻資料則甚少。

本文即針對集水區內整體性 BMP 之使用，對區內水質改善之效果做一探討。選擇科羅拉多州丹佛市附近之 West Tenmile Creek 做一實例之研究。該流域有一銅山開發區，本研究在該開發行為前、中以及完成後作水質監測及分析，結果證明該流域在全面推動 BMP 以後，對 West Tenmile Creek 之水質及棲地保護有極優良的效果。

關鍵詞：污染排放消除系統、雨水逕流、最佳管理作業、總懸浮固體物、水質保護

Introduction and Background

Since the early 1990s when Phase I of the National Pollutant Discharge Elimination System (NPDES) Stormwater Regulations went into effect in the United States, significant research has been conducted to evaluate the effectiveness of stormwater best management practices (BMPs). This type of research has proliferated since the adoption of Phase II NPDES Stormwater Regulations in 2003 since many smaller municipalities, unregulated under Phase I, are now required to have NPDES permits for stormwater discharges and face the challenges of selecting BMPs that are effective for management of non-point source (NPS) pollution and protection of receiving water quality. Internationally, awareness of the effects of NPS on receiving water quality has increased dramatically, and researchers in the United States, Asia, Europe and other population centers around the world have focused on determining how BMPs can effectively provide treatment for pollutants in stormwater runoff.

Significant progress has been made in assessing BMP effectiveness and understanding the underlying physical, chemical and biological processes that remove or transform pollutants stormwater (Water Environment Research Foundation [WERF] 2005). Resources including the International Stormwater BMP Database (www.bmpdatabase.org) (Urban Water Resources Research Council et al. 2001) and research efforts by organizations including American Society of Civil Engineers (ASCE), WERF and others provide a wealth information on BMP performance and design; however, a significant knowledge gap still exists in determining how BMP performance relates to receiving water quality (WERF 2006). Data now exist that can provide engineers with a reasonable expectation of BMP pollutant removal and effluent water quality given a targeted parameter (often TSS), anticipated BMP loading from a defined tributary area, BMP design criteria (design rainfall, water quality capture volume, release structure details, etc.) and other factors. However, determining the effects of multiple BMPs at the development or watershed-scale on the chemistry, biology and physical characteristics of receiving waters is less well documented. Determining how multiple, distributed BMPs work on a watershed scale to influence receiving water quality is an emerging research topic in water resources engineering (Wu et al. 2006, WERF 2006).

In the late 1990s, Intrawest, the owner of Copper Mountain Resort, began a large-scale expansion of the ski resort base area, including extensive construction of commercial, residential and parking facilities and work on the lower slopes of the ski mountain to improve skier access and lift facilities. West Tenmile Creek, an excellent trout fishery characterized by exceptional water quality and a healthy community of macroinvertebrates, runs through the Copper Mountain Base Area (Base Area). Additionally, the alluvium of West Tenmile Creek serves as a public water supply source, with municipal wells located less than two miles downstream of the project site. The level of water quality protection demanded by pristine receiving waters and challenging environmental settings with steep slopes, erodible soils, intense short-duration rainfall characteristics calls for regulatory requirements and voluntary practices that go beyond what is typically required for development (Earles et al. 2000), and, consequently, the proposed Base Area expansion generated a high level of public and regulatory interest and scrutiny. Figure 1 shows the general location of Copper Mountain and the West Tenmile Creek watershed. Figure 2 shows the core of the Base Area expansion project and West Lake (a central water feature and intermediate receiving water) and illustrates the proximity of the project to West Tenmile Creek.

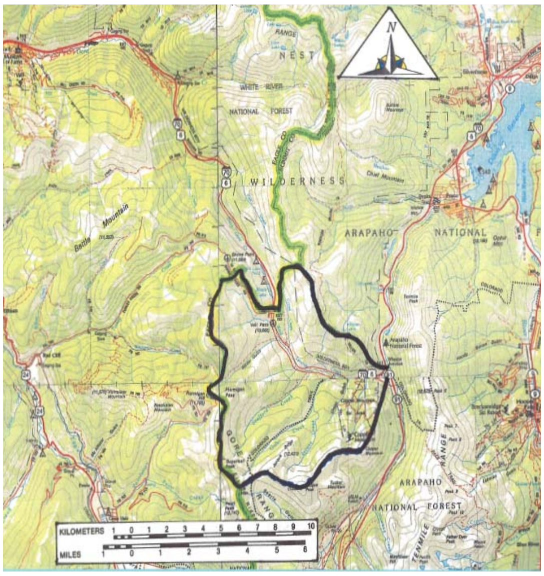

Figure 1. General Location Map and West Tenmile Creek Watershed

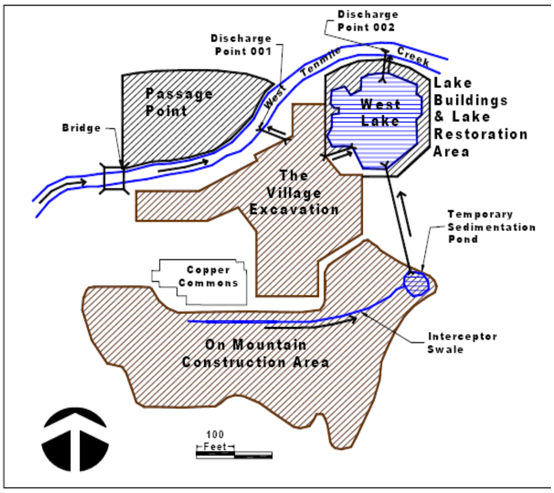

Figure 2. Copper Mountain Base Area Expansion Core

Water quality protection efforts for the Base Area expansion began with a thorough assessment of existing water quality data for West Tenmile Creek, characterization of existing and proposed land uses in the West Tenmile Creek watershed including Copper Mountain and other tributary areas, geomorphic and biological characterization of West Tenmile Creek and review of water quality criteria and other environmental regulations. Based on this information and past experiences dealing with water quality in high mountain settings with sensitive receiving waters, Wright Water Engineers, Inc. (WWE) worked with Intrawest and local regulators to develop a *Water Quality Protection Strategies* plan (WWE 1998) for the proposed expansion. This plan emphasized multiple layers of structural and non-structural BMPs and recognized the need for a multidisciplinary approach to water quality protection including input from engineers, biologists, planners, and others with expertise related to BMPs and receiving waters (Figurski et al. 2004). Concurrent with development of water quality protection strategies for the Base Area expansion, WWE and Intrawest began data collection to document baseline water quality and biological quality of West Tenmile Creek. Periodic grab samples were collected at locations upstream, in the middle of and downstream from the Base Area. Macroinvertebrate surveys were also conducted to examine the character and diversity of benthic organisms and to evaluate habitat quality. Water quality sampling and bioassessments were completed voluntarily by Intrawest and were not a regulatory requirement; however, the project team recognized the importance of baseline data for evaluating the overall effectiveness of water quality protection strategies for the development.

Construction and Challenges

The Base Area expansion at Copper Mountain consisted of multiple projects that were constructed between 1999 and 2005. At the time of publication of this paper, Intrawest is in the planning stages of a second phase of the Base Area expansion. The effectiveness of the water quality protection strategies for the phase of the development described in this paper has provided regulators and the public with a good level of comfort that a plan consisting of structural and non-structural BMPs accompanied by water quality and biological monitoring of stream health can be highly effective at protecting West Tenmile Creek.

There were multiple projects associated with Base Area expansion between 1999 and 2005, including (1) The Village buildings, four multi-unit residential buildings on a 12-acre site with 3-acres of underground parking; (2) Passage Point, a multi-unit residential development across West Tenmile Creek from The Village, including underground parking; (3) The Lake District, retail shops and a boardwalk along the boundary of West Lake; and (4) Trail's End, the Cirque and Lewis Ranch, residential construction projects ranging from multi-unit condominiums to townhomes to large lot custom homes. The Village, Passage Point and The Lake District are clustered around West Lake, shown in Figure 2, and West Lake was a common thread with respect to the water quality management strategy for all of these projects. The Village used West Lake for construction dewatering and stormwater treatment, and Passage Point took advantage of the capacity of West Lake for construction dewatering treatment. The Lake District (and West Lake Restoration associated with the project) posed one of the greatest challenges since it was necessary to dewater West Lake itself for work on footings for The Lake District and recontouring of the lake. The following sections describe some of challenges faced during construction, a period of particular vulnerability for stream biological integrity and water quality due to exposed soils and extensive construction activity.

The Village

Initial site investigations of The Village project site, as well as prior design and construction experience in the vicinity, indicated that groundwater would be encountered when excavating and constructing the parking and building foundations for The Village and Passage Point. As a result, permanent de- watering systems would be required for these buildings. Planning indicated that groundwater management during construction would be challenging for multiple reasons:

1. West Tenmile Creek, with an average annual discharge of approximately 21,000 acre-feet, was located immediately north of the construction zone, and deep excavation occurred within 40 horizontal feet of the channel.
2. The West Tenmile Creek alluvium transmits large quantities of water during the summer construction season (which corresponds to the snowmelt and thunderstorm seasons). A compounding factor was that the historic West Tenmile Creek channel (now a preferential flow path for groundwater) passed directly through the parking garage location.
3. The magnitude of the groundwater inflows to the construction zone was further increased because of the site's location at the base of the ski mountain, which produced substantial surface and subsurface flows from melting of natural and man-made snow.
4. Construction site runoff had to be managed concurrently with dewatering discharges, and it was not feasible to isolate all of the dewatering flows from Passage Point and The Village from the runoff waters of The Village and on-mountain areas.

Construction of The Village began in early May 1999. By mid-May 1999, the excavation had progressed to a depth at which groundwater was encountered and construction dewatering commenced. WWE, on behalf of Intrawest and the general contractor, obtained a Colorado Department of Public Health and Environment (CDPHE) construction dewatering discharge permit that specified two discharge locations, shown in Figure 2:

- Discharge 001 to West Tenmile Creek via a bank-side detention/filtration system.
- Discharge 002 to West Tenmile Creek via West Lake, also a primary stormwater outfall.

The general dewatering strategy was to direct "clean" dewatering discharges to a bank-side detention facility and to direct sediment-laden dewatering discharges to West Lake for extended detention and sedimentation prior to discharge. As a condition of the CDPHE construction dewatering permit, sample collection for water quality analyses for TSS, total dissolved solids (TDS), and total phosphorus (TP) was required on a weekly basis. While reporting was required for all monitored parameters, the only numeric standard for gauging compliance was TSS. The permit specified that the TSS concentration in the discharges should not exceed a concentration of 45 milligrams per liter (mg/L) for a weekly average and a concentration of 30 mg/L for a monthly average.

A variety of measures were identified and implemented to manage stormwater and construction dewatering discharges and to increase the sedimentation effectiveness of West Lake. BMPs for the Village included:

1. Alum dosage of West Lake and construction dewatering discharge flows were used as measures to enhance sedimentation. The pH of West Lake and the discharge from West Lake to West Tenmile Creek were monitored on a daily basis to assure that the alum polymer addition did not create toxic effects on aquatic life. These pH measurements indicated that there were no significant pH changes resulting from the alum polymer addition. The alum polymer was quite effective for the low-temperature/low-alkalinity groundwater encountered in this mountain setting.
2. Extensive erosion and sediment control measures were implemented upgradient of the excavation at the toe of the ski mountain. Measures included construction of a water quality swale and sedimentation pond. These preventative measures were implemented to reduce sediment entering the excavation area and West Lake. Since dewatering flows and stormwater were both routed to West Lake for treatment, it was critical to assure that sediment carried to West Lake in runoff was minimized. West Lake was specified in the dewatering discharge permit as a treatment measure prior to discharge to the receiving water (West Tenmile Creek), and, as a result, permit compliance was assessed by sampling at the outflow from West Lake. While the construction stormwater permit required the implementation and maintenance of stormwater BMPs, no numeric water quality standards were specified in the stormwater permit. The construction de- watering permit, however, specified numeric standards for TSS. Since dewatering discharges and runoff were combined in West Lake and since compliance was gauged at the outflow from West Lake, the mixture of runoff and dewatering water (rather than just the dewatering discharge) was required to meet the numeric standard for TSS specified in the dewatering permit.
3. The well point placement strategy for construction dewatering was designed to intercept clean groundwater before reaching the area of disturbance. Dewatering plans were developed to isolate well points from the excavation and activities of heavy machinery that disturb sediments and impair the quality of dewatering discharges.

4. Inflows to West Lake from West Tenmile Creek (a snowmaking diversion for resort operations) were effectively shut off, thereby increasing residence time for stormwater and dewatering discharges passing through the lake.
5. Stabilization measures were implemented on the banks of West Lake to minimize erosion of banks during storm events. Measures included installation of silt fence with a rigorous inspection regimen and application of a tackifier.
6. A diversion system was created, allowing for diversion of dewatering discharges to West Tenmile Creek (if "clean") or to West Lake (if "dirty") via manipulation of in-line valves.

Passage Point

With knowledge of the challenges encountered at The Village in 1999 and similarities between The Village and Passage Point in terms of stormwater and construction dewatering management, WWE and Intrawest carefully planned the treatment strategy for Passage Point in anticipation of similar sediment challenges. Flows from the Passage Point excavation were expected to be significantly less than from The Village, so initially, an on-site treatment pond for dewatering discharges was planned to avoid having to convey dewatering discharges across West Tenmile Creek to West Lake for treatment. Based on the experiences with The Village in 1999, a contingency plan was developed and supplies were gathered so that they would be on hand if needed. The contingency involved pumping the dewatering discharge across West Tenmile Creek to West Lake for treatment. The contractor purchased additional alum polymer for use if necessary.

It was fortunate that these contingency plans were developed since the on-site pond was not effective enough at removing suspended sediments to meet permit requirements. When the on-site pond proved ineffective, a treatment system analogous to the 1999 Village system was implemented. This included directing "dirty" water to West Lake and "clean" water to a bankside filtration /detention facility using a diversion. Alum polymer treatment was set up at the point of discharge to West Lake (good mixing at the point of discharge). This system proved effective again during the summer 2000.

The Lake District and West Lake Rehabilitation

West Lake served the project well during 1999 and 2000, but with dewatering of West Lake required for The Lake District and West Lake Restoration, an alternate strategy was needed for 2001. Since The Lake District was the final stage of The Village and associated projects, space for treatment was scarce.

WWE worked with Intrawest to develop a treatment strategy using a pond-within-a-pond approach. Two ponds, one for stormwater runoff and one for construction dewater discharges, were planned to be constructed on the bottom

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of West Lake and positioned to allow dewatering in areas where footings needed to be poured for The Lake District, or where work on the banks of West Lake was necessary. Water from the permanent foundation drain system for The Village, which flows to West Lake, was rerouted to discharge to the stormwater pond to maximize residence time in the dewatering pond. A polymer for enhanced sedimentation was obtained by the contractor as a contingency.

Construction of the ponds within West Lake presented a logistical challenge since West Lake had to be dewatered to create the ponds. During construction of the ponds in West Lake an alternate dewatering treatment method was needed. West Lake was first drawn down via gravity as far as possible (not regulated by dewatering permit). For pumped dewatering discharges (regulated by the dewatering permit), treatment was provided via filtration. Dewatering discharges from West Lake were pumped into a “dewatering bag” constructed of a biodegradable geotextile fabric. Flow rates were kept as low as practical to minimize the loading on the filter bags, and dewatering discharges were drawn from near the surface of the lake to draw out water with the least sediment in it. Bags were replaced approximately monthly, or as soon as elevated sediment levels (evidenced by slight discoloration) were observed in the discharge. The pump intake was attached to a small paddleboat, tethered to the banks with rope. This set-up allowed the contractor to move the intake point around the lake to draw in the cleanest water. These techniques proved highly effective at providing water quality protection while the ponds were constructed in West Lake.

West Tenmile Creek Setback Enhancement

During the construction of the Trail’s End portion of the base area development at Copper Mountain (north of the Village Core), a development constraint was maintaining good access for the heavily used bike path on the south side of the development running along West Tenmile Creek and heading up to Vail Pass. To construct a suitable alignment, several areas of encroachment into the wetland and riparian area buffer along West Tenmile Creek were necessary. Important purposes of wetland and riparian buffers are to provide water quality protection and wildlife and habitat benefits. To offset buffer encroachments and to actually improve the function of the buffer, Intrawest developed a *Wetland Setback Encroachment Mitigation and Enhancement Plan* (WWE 2003). This plan identified portions of the buffer that were in relatively poor condition prior to the start of the project and targeted them for enhancement. Enhancement measures involved planting wetland plants including willows and various shrubs and planting transitional and upland areas within the buffer with shrubs and native grasses. Intrawest consulted with the United States Army Corps of Engineers and the Colorado Division of Wildlife on this project. Follow-up monitoring of enhancement areas has demonstrated that the project has been a success.

MEASURING SUCCESS—ASSESSMENTS OF STREAM BIOLOGY AND WATER QUALITY

Biological Monitoring

Biological monitoring of West Tenmile Creek was conducted prior to the start of construction in 1999, during the construction phase of The Village and Passage Point in 2000 and most recently in 2005. Four locations were selected for biological monitoring: one site upstream of Copper Mountain, two sites within the resort Base Area (upstream and downstream of a primary tributary, Wheeler Gulch), and one site downstream of con- struction activities. The approximate locations of these sites along with water quality sampling locations are shown on Figure 3.

During each biological survey, WWE collected sample of benthic macroinvertebrates and performed a habitat assessment. Benthic macroinvertebrates were sampled using standard procedures (USEPA 1998), and habitat types were sampled in proportion to their occurrence over an approximately 50-meter reach at each site. Samples were preserved in the field, and a 100-organism sub-sample was created from each sample. Organisms were identified to the genus level or the lowest taxonomic level possible. The taxonomic guides used were Merritt and Cummings (1988) and Ward and Kondratieff (1992).

Habitat quality was evaluated following the habitat assessment procedure in USEPA guidance (USEPA 1998). Habitat quality was assessed by completing a "habitat assessment field data sheet—high gradient streams" at each site. This entailed rating habitat quality in terms of ten parameters that address flow conditions, in-stream habitat quality, and riparian zone conditions. Parameters were rated on a scale from 0 to 20, with 20 being "optimal." The total habitat score possible was 200. However, the total score was not as important as the relative differences between scores.

Habitat Assessment

West Tenmile Creek has a moderate gradient that becomes flatter in the study area. In-stream and riparian habitat are similar at sites where the creek channel has not been altered, primarily upstream of the Base Area development. The creek channel at the more upstream sites (WTC-1 and WTC-2) was armored by large cobble and boulders through a riparian corridor dominated largely by willows. In-stream habitat at these sites consisted principally of riffle habitat, with pockets of slower water near the shoreline and behind larger boulders. Substrate was relatively clean, though a thin layer of brown sediment was observed in slower areas along the shoreline. A substantial amount of coarse particulate organic matter in the form of relatively recent leaf fall existed at these sites.

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One of the sites monitored was directly downstream of The Village (WTC-3) and downstream of West Lake. The creek downstream of WTC-3 is a lower gradient riffle/run armored by large cobbles and boulders. A thin layer of fine sediment was observed in slow water along the shore. The creek channel has been altered in this reach and the riparian zone encroached by a road and base area landscaping.

WTC-4 was located on the golf course, downstream of the Base Area development. The stream gradient was flatter at this location. This site included more shallow pool habitat. Shallow riffle habitat was sampled at the upstream portion of this site. Substrate at this site was smaller than the upstream sites, and consisted largely of cobble.

Table 1 shows the habitat assessment scores for both the May 2000 and 2005 bioassessments.

Table 1. Habitat Assessment Scores for Bioassessment Sites—West Tenmile Creek

Metric	WTC-1 5/2000	WTC-1 9/2005	WTC-2 5/2000	WTC-2 9/2005	WTC-3 5/2000	WTC-3 9/2005	WTC-4 5/2000	WTC-4 9/2005
Epifaunal substrate/available cover	20	10	20	20	20	20	20	20
Embeddedness	19	19	19	19	18	19	13	19
Velocity/depth regime	13	14	13	13	13	13	17	17
Sediment deposition	20	19	19	19	19	19	13	17
Channel flow status	19	18	20	19	18	17	20	12
Channel alteration	20	20	20	20	15	13	18	18
Frequency of riffles	20	20	20	20	20	20	20	20
Bank stability	20	20	18	18	18	19	18	19
Vegetative protection	20	20	19	19	10	12	14	15
Riparian vegetative zone	17	17	12	13	8	8	10	10
TOTAL SCORE	188	187	180	180	159	160	163	167

Habitat ratings were similar for both bioassessments. Overall, habitat quality was good to excellent at all the sampling sites. All sites had good available substrate and channel stability.

Benthic Organisms

The results of the metrics that describe the nature of the benthic community are shown in Table 2 for both the May 2000 and the 2005 bioassessments.

Table 2. Tenmile Creek Bioassessment Summary of Benthic Sampling Results

Metric	WTC-1 5/2000	WTC-1 9/2005	WTC-2 5/2000	WTC-2 9/2005	WTC-3 5/2000	WTC-3 9/2005	WTC-4 5/2000	WTC-4 9/2005
Taxa richness	22	15	18	11	15	12	11	19
EPT Index	16	9	12	4	10	5	8	12
Percent contribution of dominant taxon	19	29	35	33	64	33	45	36
Scraper-filtering collector ratio	0.4	0.6	0.6	0.4	0.25	1.1	0	0.9
EPT-Chironomidae ratio	3.9	31.0	25.5	9.0	30.7	0.9	*	3.4
Modified HBI	3.4	4.0	2.9	4.0	3.1	4.7	2.4	3.7

Notes: EPT= Ephemeroptera-Plecoptera-Trichoptera; HBI= Hilsenhoff Biotic Index

*No chironomids found

In general, a healthy benthic community was found at each of the sampling sites typical of those found in similar creeks in the state. The community was dominated by mayflies, stoneflies, and caddisflies at each site. However, the characteristics of the benthic community varied between the sampling sites in terms of the dominant species present and the pollution tolerance of the organisms.

The following observations were made regarding differences between the sampling sites in 2005:

- The greatest number of species, referred to as taxa richness, was found at WTC-1 and WTC-4. The higher number of species found at WTC-4 may be due to the greater variety of habitat types available at the site. Several species of mayflies, stoneflies and caddisflies, all of which are relatively more sensitive, were found at WTC-4.
- The trend for the EPT index, which is the number of species in the mayfly, caddisfly, and stonefly orders, followed a similar trend to taxa richness.
- The percent contribution of the dominant taxon was relatively constant at all sites. This metric was slightly lower at WTC-1, which indicates a healthier benthic community. The dominant species at sites WTC-1, WTC-2, and WTC-4 were either mayflies (family Baetidae) or riffle beetles (family Elmidae). The dominant species at WTC-3 were chironomids.
- The EPT-chironomidae ratio, which is the number of mayflies, stoneflies, and caddisflies (relatively sensitive organisms) to the number of chironomids (more tolerant organisms), varied greatly between the sites. This ratio was the highest (indicating the

healthiest community) at WTC-1 and lowest at WTC-3, where chironomids were the most common organism.

- The Hilsenhoff Biotic Index (HBI) was relatively similar between the sites. This metric was the lowest (had the most sensitive community) at WTC-4 and was highest at WTC-3 where the benthic community was more tolerant.
- The ratio of scraper to filtering collectors is a measure of the food base available for benthic organisms. This ratio was relatively constant between sites and was highest at WTC-3.

Although the same methodology was used for the 2000 and 2005 bioassments, results from the two dates are relatively different. These differences may be due to several factors, the most important of which is the different time of year of the sampling. Samples were collected in the spring of 2000 versus the fall of 2005. Past studies have shown relatively large changes in the benthic community on a seasonal basis. Another factor to consider is that historic drought conditions occurred between the sampling times. This may have resulted in relatively low flows, increased water temperatures, and other changes that could have affected the benthic community. The following observations are made with regard to results from the two sampling efforts.

- Taxa richness was higher at most of the sites in 2000. The same was found with the EPT index.
- The percent contribution of the dominant taxon was generally lower in 2005, indicating a more balanced community structure. There is also less variation in this metric in 2005.

- The scrapering-filtering collector ratio was relatively similar between both sampling times. This suggests a relatively stable food base in the creek.

- Large differences were found in the EPT-chironomidae ratio between the sampling dates. A relatively large number of chironomids were found at WTC-1 and WTC-3 in 2000. Chironomids favor soft sediment, which may have been more prevalent in the previous sampling.

- Values of the HBI were higher, indicating a more tolerant benthic community, at all sites in 2005. This indicates that the community became more tolerant between these two dates.

- Riffle beetles from the family Elmidae were relatively rare in 2000, but comprised a significant proportion of the community at the sites in 2005. No explanation is readily apparent for this finding.

Discussion and Evaluation of Biological Monitoring Results

The benthic organism sampling of 2005 showed differences between sample locations and differences relative to the previous sampling in 2000. During both sampling efforts, a healthy benthic community, dominated largely by mayflies, stoneflies and caddisflies, was found at all sites. The spring versus fall sampling, and occurrence of significant drought conditions between the sampling times, may explain the differences between sampling events.

In the 2000 sampling results, the benthic community health was better correlated with habitat quality. In 2002, the most robust benthic community was generally found at WTC-1, which also had the highest habitat score, and the health of the community declined with decreasing habitat quality. Also, there was more variation in the metric values in 2000.

Another finding that is not readily explained is the prevalence of riffle beetles from the family Elmidae in 2005. These beetles only occurred in relatively low numbers in 2000, but were the first or second most dominant species in 2005. Several species of Elmidae beetles live in Colorado. All occur in riffle habitat and are moderately sensitive. No conditions were identified that would explain their increased dominance.

A relatively fine film of sediment was observed in slow water areas at each site in 2005. Sediment typically encourages midges (from the family Chironomidae) and other more tolerant species; however, adjacent cobble and boulder habitat in flowing water was clean, encouraging more sensitive species. Because both types of habitat were sampled, a mix of both sensitive and more tolerant species was found. This is consistent with results from other bioassessments in similar settings throughout Colorado.

While the results of the second bio- assessment raise some questions regarding the nature of the benthic community in West Tenmile Creek, neither sampling event shows any significant impairment of the benthic community. The presence of some more tolerant species may be due to the relatively small amount of fine sediment in slow water at the sampling sites. The presence of very sensitive species at each site, including mayflies from the families Ameletidae and Ephemerellidae, stoneflies from the family Leuctridae, and caddisflies from Rhyacophillidae, indicate that excellent water quality conditions exist in West Tenmile Creek in the study area.

Water Quality Monitoring

From May through August 2006, Wright Water Engineers, Inc. (WWE) staff collected monthly synoptic samples from West Tenmile Creek at five locations ranging from above the Copper Mountain Resort to just above the confluence with Tenmile Creek. The purpose of this sampling effort was to evaluate water quality conditions for the stream through the Base Area and to determine if the construction activities and developmet from 1999 to 2005 and existing resort conditions appeared to be having any adverse impacts on water quality. Similar data were analyzed when the *Water Quality Protection Strategies* plan was developed prior to the start of construction in 1999, and data at that time indicated excellent water quality and compliance with water quality standards established for West Tenmile Creek by the Colorado Water Quality Control Commission (CWQCC).

Water quality sampling locations are shown on Figure 3. The stations labeled on Figure 3 as “Above I-70,” “Below Union,” “Above Wheeler” and Above Confluence roughly corresponded to biological monitoring locations WT-1, WT-2, WT-3 and WT-4, respectively. Table 3 contains a summary of the sampling results. Key results of water quality monitoring included:

- Water quality can be characterized as excellent. During all site visits, flows were clear, with no significant sediment loading evident. No decrease in water quality occurred from above Copper Mountain Resort to below the resort.
- Nutrients, including ammonia, nitrate, nitrite, dissolved phosphorus and total phosphorus were consistently below detection limits, with the exception of one nitrate sample that was slightly above detection limits, but well below the stream standard. WWE requested a lower detection limit for phosphorus analyses in July and the laboratory was able to report “J” qualified values for the last two sampling events that reflect estimated values below the reportable detection limit. No “J” values were reported for August 31 and “J” qualified values of 0.02 or 0.03 mg/L were reported for total phosphorus during the August 1 sample event at all sample locations, including upstream of the resort. One “J” value was reported for dissolved phosphorus upstream of I-70 on August 2, 2006, but in no other samples. These data indicate that the resort does not appear to be increasing the phosphorus loading to West Tenmile Creek.
- Dissolved oxygen (DO) averaged 7.6 mg/L, with no measurement below CWQCC stream standards.
- The average pH was 8 and remained consistent (standard deviation = 0.2) and met CWQCC stream standards through all sampling events, with no upstream to downstream trend.
- Total suspended solids (TSS) were below the detection limit of 5 mg/L at all locations and for all sample events, with the exception of one low detected value of 6.5 mg/L above Wheeler Gulch in May.

Figure 3. Water Quality Sampling Locations and Approximate Locations of Biological Surveys

The original sampling plan for metals included analyses for metals with assigned CWQCC stream standards at the confluence location during the May and September sampling events. All metals were analyzed in the dissolved form, with the exception of total mercury, total recoverable iron and total recoverable arsenic. Metal samples were collected in May at this location and planned for collection in September. However, the laboratory inadvertently analyzed metals at all locations in the August 1, 2006 sample.. (For this reason, September samples were not analyzed for metals.) Of the 12 metals for which analyses were conducted, all were below detection limits at all sample locations in August, with the exception of copper, iron and manganese, which had a few detectable concentrations. On August 1, copper concentrations were above the stream standard upstream of Copper Mountain and below Union Creek but were below detection limits at all other locations. Manganese

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was detected at a few locations, but was well below the stream standard. Total recoverable iron was reported at the detection limit and well below the stream standard at the confluence monitoring location in May.

These samples were collected during dry weather flow conditions, but were collected over a time period that reflects the spring run-off, followed by gradually decreasing flow conditions in the later summer. Relative to the annual hydrograph, the four sampling events would be considered to be a high flow period.

Conclusions

The multi-tiered program developed in the *Water Quality Protection Strategies* plan for the Base Area development at Copper Mountain provides an example of a successful BMP -based approach to water quality protection for development, both during construction and operational phases. A unique aspect of this project has been the extensive documentation of water quality and biological characteristics of West Tenmile Creek. While many evaluations of BMP effectiveness focus on BMP inflows and outflows and provide useful information on the processes that remove pollutants in BMPs, the monitoring data collected at Copper Mountain provides a broader perspective and demonstrates how a development-wide system of structural and non-structural BMPs can be effective at protecting water quality. The water quality and biological data collected before during and after the construction of the Base Area expansion demonstrate that receiving water quality of West Tenmile Creek has been protected.

Table 3. West Tenmile Creek 2006 Water Quality Data

Location	Date	NH_3-N	Conduc-tivity	P, Diss.	DO	Hard-ness	NO_3-N	NO_2-N	pH	P, Tot.	Temp	TSS	As, Trec.	Cd	Cr	Cu	Fe, Trec.	Pb	Mn	Hg, Tot.	Se
Units		mg/L	us/cm	mg/L	mg/L	mg/L	mg/L	mg/L	SU	mg/L	C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Above 70	10-May-06	<0.8	NA	<0.1		68	<0.056	<0.076	8.1	<0.1		<5									
Above 70	21-Jun-06	<0.8	130	<0.1	7.3	53	<0.056	<0.076	7.6	<0.1	9.2	<5									
Above 70	02-Aug-06	<0.8	192	0.02J	7.2	79	<0.056	<0.076	7.7	0.021	9.7	<5		<0.01	<0.01	0.0190		<0.073	0.0098		<0.1
Above 70	31-Aug-06	<0.8	222	<0.1	7.5	99	<0.056	<0.076	8.1	<0.1	7.6	<5									
Above Wheeler	10-May-06	<0.8	NA	<0.1	NA	74	<0.056	<0.076	8.1	<0.1	NA	6.5									
Above Wheeler	21-Jun-06	<0.8	131	<0.1	7.7	53	<0.056	<0.076	7.9	<0.1	9.9	<5									
Above Wheeler	02-Aug-06	<0.8	131	<0.1	8.0	82	<0.056	<0.076	7.9	0.021	10.0	<5		<0.01	<0.01	<0.005		<0.073	<0.005		<0.1
Above Wheeler	31-Aug-06	<0.8	222	<0.1	8.3	97	<0.056	<0.076	8.1	<0.1	7.3	<5									
Below Union	10-May-06	<0.8	NA	<0.1	NA	68	<0.056	<0.076	8.1	<0.1	NA	<5									
Below Union	21-Jun-06	<0.8	128	<0.1	7.7	53	<0.056	<0.076	7.6	<0.1	9.7	<5									
Below Union	02-Aug-06	<0.8	192	<0.1	7.3	79	<0.056	<0.076	7.9	0.021	10.0	<5		<0.01	<0.01	0.0098		<0.073	0.0066		<0.1
Below Union	31-Aug-06	<0.8	221	<0.1	7.6	97	<0.056	<0.076	8.1	<0.1	8.0	<5									
Below Wheeler	10-May-06	<0.8	NA	<0.1	NA	74	<0.056	<0.076	8.2	<0.1	NA	<5									
Below Wheeler	21-Jun-06	<0.8	149	<0.1	7.5	60	<0.056	<0.076	7.9	<0.1	9.5	<5									
Below Wheeler	02-Aug-06	<0.8	198	<0.1	7.6	83	<0.056	<0.076	8.1	0.021	10.0	<5		<0.01	<0.01	<0.005		<0.073	<0.005		<0.1
Below Wheeler	31-Aug-06	<0.8	221	<0.1	8.1	98	<0.056	<0.076	8.2	<0.1	7.6	<5									
Confluence	10-May-06	<0.8	NA	<0.1	NA	74	0.059	<0.076	8.2	<0.1	NA	<5	<0.05	<0.01	<0.01	<0.005	0.07	<0.073	0.0066	<0.0001	<0.1
Confluence	21-Jun-06	<0.8	137	<0.1	7.1	57	<0.056	<0.076	7.8	<0.1	10.2	<5									
Confluence	02-Aug-06	<0.8	178	<0.1	7.2	82	<0.056	<0.076	8.0	0.031	10.0	<5		<0.01	<0.01	<0.005		<0.073	<0.005		<0.1
Confluence	31-Aug-06	<0.8	223	<0.1	7.6	98	<0.056	<0.076	8.2	<0.1	8.7	<5									
Average		<0.8*	178	<0.1*	7.6	76	<0.056*	<0.076*	8.0	<0.1*	9.2	<5	<0.05	<0.01*	<0.01*	0.0048	0.07	<0.073*	0.0038	<0.0001*	<0.1*
Minimum		<0.8*	128	<0.1*	7.1	53	<0.056*	<0.076*	7.6	<0.1*	7.3	<5		<0.01*	<0.01*	<0.005	NC	<0.073*	<0.005	<0.0001*	<0.1*
Maximum		<0.8*	223	0.02J	8.3	99	0.059	<0.076*	8.2	0.031	10.2	6.5		<0.01*	<0.01*	0.019	NC	<0.073*	0.0098	<0.0001*	<0.1*
Std. Dev.			40		0.3	16			0.2		1.0										

J = Value reported below Practical Quantification Limit at Request of WWE

<__*=all values below detection limits

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WERC

Technical Paper

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Tools and Processes for Implementing a Road Ecology Approach to Transportation and the Environment

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Abstract

Road systems are an essential infrastructure need for economic and social wellbeing. As road networks expand and alter the landscape, ecological processes are affected, in turn affecting core resources such as water quality, air quality, wildlife habitat, fisheries, wetlands and vegetation. Awareness of the effects of roads on the environment has grown, but research is still needed to achieve a scientific understanding of the underlying processes and to apply this understanding to the design of sustainable transportation systems.

The science of road ecology is being developed to address the interface between roads and natural systems. Scientific research will provide the foundation for development of a road ecology approach to transportation systems. The road ecology approach will include tools and processes that incorporate ecological considerations in transportation planning, design and project delivery. Road ecologists also aim to develop ways that transportation agencies and resource protection agencies can collaborate to lessen the impacts of roads on the environment.

Road ecology is an emerging field, both in transportation planning and engineering on the one hand, and in academic research. Several major publications worth noting have appeared in recent years. The keystone book in this area is Road Ecology (Forman et al. 2003), which provides an excellent foundation and overview of the key concepts of road ecology. A report addressing potential assessment tools and approaches, sponsored by the U.S. National Academy of Sciences (Assessing

and Managing the Ecological Impacts of Paved Roads, 2005) is available from National Academy Press (http://www.nap.edu/catalog/11535.html . Most recently, Davenport and Davenport (2006) bring together a series of papers on transportation impacts on ecosystems, ranging from marine travel to highway transportation. Several chapters deal with wildlife impacts, and include practical solutions.

The intent of this review is to summarize some recent tools and processes that may be useful and adaptable for a range of transportation planning situations. The topics include:

I、 *Ecological approaches to management of roadside soils and vegetation;*
II、 *Identifying and mitigating road impacts on wildlife;*
III、 *Eco-Logical, an integrative planning tool for professionals;*
IV、 *University Centers for environment and transportation; and*
V、 *ICOET, the International Conference on Ecology and Transportation.*

Keywords: Road ecology; Transportation

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簡論推行道路生態規劃的一些工具及方法

道路系統為社會經濟民生福祉不可或缺設施之一，在道路網絡不斷擴充情況下，沿路之景觀及生態將會受影響，而對重要資源，如水、空氣、野生動物棲地、漁產、濕地及植物等引起衝擊。目前道路會對環境產生影響已被認同，但有關對何種影響細節之瞭解，以及如何將瞭解後得到之資訊應用到設計規劃一永續性之交通系統等方面之研究則仍有待加強。

道路生態領域現在仍正在發展中，其內涵是道路與自然系統介面之探討，而目的則是建立已含生態考量之交通系統規劃之基礎並提供考量生態的一些工具及方法。道路生態之另一目標為促進交通及資源部門之合作來減輕道路對環境引起之衝擊。

目前，在交通規劃、工程及學術研究方面，道路生態之考量還僅是在起步階段。近幾年來，有一些重要的文獻值得參考：

- Forman 等（2003）所著的書「道路生態」，對道路生態之重要基礎及觀念有詳盡之描述。
- 美國國家科學院 2005 年的一本報告「鋪面道路對生態衝擊之評估及管理」，（http://www.nap.edu/catalog/11535.html.）介紹了一些評估工具及管理方法。
- Davenport and Davenport（2006）發表了一系列之論文，內容主要為交通（航運、公路等）對生態系統之衝擊，包括對野生動物之影響及實務的解決方法等。

本文之目的為討論在交通規劃中考量到路生態的一些工具及方法，內容包括：

I、 *保護生態之路邊土壤及植物的管理*
II、 *道路對野生動物衝擊之鑑定及減輕方法*
III、 *Eco-Logical，進行實務工作時整體性規劃工具*
IV、 *大學中環境及通研究中心簡介*
V、 *ICOET，國際生態及交通研討會*

關鍵詞：道路生態、交通規劃

Part I. Regenerating functional soils to support native plants for slope stabilization

Soil erosion along roads is a severe problem in many parts of the world, particularly where roads intersect with sloping topography, and where environmental disturbances such as heavy rainfall or fire can lead to excessive runoff and destabilization. To identify and remediate the causes of non-point source erosion on drastically disturbed slopes (meaning all topsoil and biological material removed by excavation, landslide or burial), soil scientists at the Soil and Revegetation Laboratory (University of California, Davis) have developed a set of guidelines that focus on soil stabilization as a starting point. Thus, if the soil or substrate conditions are made adequate, many locally occurring plant species will colonize and stabilize the slopes, bringing their associated tolerances for local climatic conditions, grazing pressure and disease. This is an alternative to approaches that emphasize single-species plantings that may be adapted to some conditions, but that can become either weedy invaders in other local habitats, or that do not survive during periodic weather extremes.

Each of the target soil characteristics must be measured in ways that are relevant to wildlands conditions (as opposed to agricultural conditions) and that have known or adaptable treatments that can be constructed by heavy equipment. While many soils tests have been developed for horticultural, agricultural or forestry uses, these may not be useful in degraded substrates. Also, in order for implementation to occur, the treatments specified must be cost effective to purchase, transport and apply to sites that are often remote, and difficult to work (steep, unstable, rocky or clayey).

The guidelines, as currently developed, include:

1) identification of a reference site;
2) evaluation of infiltration capacity;
3) assessment of plant available water;
4) knowledge of soil organic matter pools and mineralization rates of C and N;
5) non-N nutrients and soil chemical characteristics (pH, CEC, EC);
6) soil biological activity (symbiotic microbes, saprophyte activity);
7) surface erosion stabilization; and
8) needs for site specific plant materials.

1. **Reference sites** are selected that represent the potential outcomes within 3 to 5 or 10 years after construction. The purpose is to envision what outcomes are acceptable to the stakeholders and to make sure that everyone is agreeing on the same result. The reference site also serves as an example of a soil / plant system that works well in the local environment and can be used to develop target soil characteristics. Typically, a “disturbed-but-revegetated” site is preferable to an “undisturbed” site, since less disturbed sites often have soil

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materials that have developed or accumulated for hundreds to thousands of years, making an unrealistic target for a short term revegetation project. Plant community density and composition are often evaluated on the revegetated reference and the impacted (barren) sites, but actual measurement of soil conditions is made on both sites through the remaining soil evaluation steps.

2. **Infiltration rates** for impacted sites are often reduced because the fine mineral particles often settle and pack tightly or form crusts due to the low organic matter content. This reduces downward infilt- ration of rainfall, causing more water to flow over the surface of the site. Our approach to this situation is to set a target condition for infiltration that is adequate to prevent overland flow at the site. This can be done by copying the characteristics of the revegetated reference site, or by getting a rate from storm intensity data for various storm return frequencies. When the site is tilled or ripped with heavy equipment, the soil particles often re-settle back into a close packed configuration within a season or so, returning the site to an erosive condition. Incorporation of coarse woody material (forest thinning slash, unscreened yard waste compost, tub ground (not chipped) wood) helps keep the soil macropores open for the several years needed to start regeneration of soil structure.

3. **Threshold levels** for plant available water is estimated from evapotranspiration data and plant water use data of native grasses and shrubs. The amount of soil needed for adequate plant moisture varies widely, but is typically between 0.5 m and 1.5 m, depending on the rock content of the soil, which can dilute the water holding capacity. It is not necessary to till to this depth, if the underlying geology is already fractured, which is common in many rock types.

4. **Soil organic matter** is important for generating soil aggregates, as mentioned in the infiltration section, but also for providing a long-term supply of nitrogen (N) for plant growth. Fertilizer applications of nutrients, especially of N, tend to be highly available for a short period, encouraging weedy growth. Shortly thereafter, available N declines and the plant community thins and erosion returns. Amending the site with large loads of composted materials (50 to 100 Mg or more) can supply a long-lasting but slowly available supply of N for regeneration of the plant community. Note that regeneration of the community on a previously barren site requires not only N for the plant biomass, but for soil organic matter, secondary woody tissue, a woody duff layer, and for all the soil biota that will colonize the site. This may require many hundreds of kg N/ha to be available for incorporation into living or dead biomass.

5. **Non-N nutrient evaluation** (P, K, S, Ca, Mg, micronutrients) and soil chemical characteristics (pH, CEC, EC) are generally easily measured by existing soil fertility tests. Target values, however, are set for wildlands systems rather than for commercial agricultural systems. When this information is not available, we again use the revegetated reference site to indicate what is adequate for the plants growing in this environment.

6. **Soil biological activity** is divided into saprophytic groups, which are generally easily stimulated by organic matter additions, and to symbiotic microbes, including N-fixing symbionts and mycorrhizal fungi. These goals are very site specific and cannot easily be generalized except to say that we emphasize the use of locally collected inoculants, which have been exposed to local climatic conditions for an extended period of time and are hopefully adapted to these conditions.

7. **Surface stabilization** involves either temporary erosion control, long term erosion control or surface mulch effects. Temporary erosion control is a well-developed commercial activity, making available many products and approaches. We note that if infiltration is regenerated, much less emphasis can be placed on surface erosion control efforts, since overland flow is predominantly eliminated. Long term erosion control involves controlling water from running onto the site from upslope, undercutting the toe of slopes, and making sure that the vegetative community is vibrant and dense enough to take on the task of protecting the soil. Mulch effects are commonly known for intercepting rain drop splash impact, but thermal protection (from winter cold and from summer heat) are also important, as is reduction in evapotranspiration from the soil during dry seasons.

8. The final aspect that has become important as we take on progressively more harsh and atypical sites is the issue of **selecting site adapted plant materials**. For valley locations and moderate climates, many horticultural accessions are available, but as the site conditions become more extreme, the need is greater to have plants that can tolerate these conditions. For these reasons, we try to identify conditions that will require special plant selection, so that these seed sources can be collected and propagated in preparation for the site treatment.

Some horticultural and agricultural plants can become weedy and invasive if planted in highly disturbed sites such as roadsides. There are current efforts to develop appropriate practices for **restoration and maintenance of native vegetation** along roadsides, as described in Harper-Lore and Wilson (2000). To insure the establishment of site-adapted native genotypes, restoration may involve a phase of propagating seeds collected from the restoration site, and then placement of the resulting plants or the next generation of seeds. Since vegetation provides habitat for wildlife, roadside plantings can have positive effects on wildlife. At the same time, precautions need to be taken to prevent creating a wildlife "sink" due to road mortality. More study in this area is needed.

Part II. Identifying and mitigating road impacts on wildlife

Road networks have been built without consideration of wildlife movement networks and as a result, often disrupt the movement of various species and negatively impact the health of the ecosystems that support their survival. From the perspective of wildlife biologists, road networks pose a threat to the health and survival of wildlife by placing barriers across wildlife movement corridors, introducing noise, toxic run-off and death from crashes. From the perspective of transportation agencies, wildlife attempting to cross roads is a safety hazard to the traveling public. Transportation agencies are also increasingly seeking ways to balance their mission of providing roads with good stewardship of the environment.

To address these concerns about wildlife and highway interactions, a variety of techniques and tools are being developed. These include approaches directed at wildlife and how they behave such as building wildlife crossing structures over or under roads, enhancing the vegetation around the crossing structures to attract and protect wildlife as they cross, removing vegetation in some areas to discourage wildlife from approaching the road, and studying the width of medians and how that affects the likelihood of wildlife to cross roads.

Traffic volume impacts to terrestrial and aquatic species

A major difference between road effects to terrestrial and aquatic organisms is traffic volume. Traffic volume, considered daily or annually when the species of interest are active, is predictive of the impact a road will have on terrestrial species (Van Langevelde and Jaarsma 2005). As traffic volume increases, roads affect wildlife species in different ways (Müller and Berthoud 1995, Jacobson in prep.). At very low traffic volume, most animals except very slow species are minimally affected, but these slow species can be wiped out if the impact continues over time. At moderate traffic volume (between 2000-8000 ADT), mortality is heaviest for most species, and habitat permeability is moderately impacted. Again, slow species will continue to experience heavy mortality as well as barrier effects. At high traffic volumes, above 8000 ADT, mortality is reduced because most animals are intimidated from attempting to cross, but the highway becomes a virtually complete barrier to animal movement. Only those species with great motivation to cross will continue to attempt to cross at very high traffic volumes. Examples include migratory deer herds, or species whose behavior is more instinctual than intelligent such as frogs and turtles.

Impacts to animals from highways vary by species. The groups of species most at risk are slow species of all taxonomic categories, such as turtles, frogs, badgers, and gallinaceous birds. This is because it takes them longer to cross a road and exposes them to risk of mortality longer. Species whose defense mechanisms are incompatible with vehicles are at great risk as well. These include species such as snakes that coil in the presence of danger, small animals that depend on cryptic coloration and motionlessness to avoid predation, and species that have circuitous travels such as rabbits. Other categories are those that must travel across highways to meet key survival needs, such as winter range, or daily water or food. Wide-ranging mobile species, including most species of carnivores, are at risk because their mobility places them in frequent contact with roads.

Traffic calming to address road impacts to terrestrial species

Because traffic volume is the best predictor of impacts to terrestrial species, any measures taken to reduce traffic volume will benefit them (Jaarsma and Willems 2002). This includes transit options, traffic calming mechanisms and installing wildlife passages on roads with predicted increases in traffic volume on existing roads. A useful traffic calming approach is to focus high traffic volume on one road instead of dispersing it among many roads. Focusing traffic volume on few roads allows mitigation to be more efficiently focused as well. Generally, roads with moderate traffic volume in high quality habitat are the highest priority for urgent and best mitigation measures such as wildlife passages and barrier fencing. Very high volume roads may be able to avoid fencing unless migrant species are present, but need wildlife passages to mitigate the impacts of loss of habitat connectivity.

Wildlife crossings

The most effective mitigation measure currently known for both mortality and habitat fragmentation impacts is a combination of wildlife crossing structures of the appropriate design for the species impacted, barrier fencing to divert them from the road into the structure, and escape structures to allow any clever animals to leave the highway if they find their way onto it (Forman et al. 2003, Clevenger et al. 2001b). Further, a mixture of large crossings for large mammals and more frequent smaller structures for smaller animals will reduce mortality and increase the permeability of the highway for most terrestrial species (Clevenger and Waltho 2000, Clevenger et al. 2001a).

Collaboration among all agencies and non-governmental organizations is key to the success of maintaining aquatic and terrestrial species health. A road does not affect only those species that wander onto its surface, but rather it can affect species far beyond it. This suggests that landowners distant from the road will benefit from involvement in transportation planning, and the public in general will be able to maintain its wildlife and fisheries resources.

The training course, Innovative Approaches to Wildlife and Highway Interactions was based on the premise that many disciplines will need to be integrated into transportation planning to solve some of the major challenges associated with highway impacts to wildlife. A key component of the short course is to include the skills and experience of both engineers and biologists, who tend to view challenges differently and have different methods of problem solving. Networking is also a useful component of these training sessions, because often professionals are unaware of other agencies' organizational structures or how to contact the appropriate person within another agency.

Additional wildlife crossing guidance

Designing crossing structures is most efficiently done when considering all the species, aquatic and terrestrial, in a geographic area. Some aquatic organism passage techniques are detrimental to wildlife passage, and can be so expensive as to preclude subsequent modification to allow for wildlife use. This may happen when a crossing is considered impactive to fisheries but the traffic volume is not impactive to wildlife at the time of planning and construction, but later the road evolves into a higher traffic volume or fun- ctional class that will affect wildlife. Crossing types designed to be functional for both aquatics and terrestrial passage over time will save money in the long run. Two websites which provide some guidance on wildlife and aquatics passage are the Wildlife Crossings Toolkit at http://www. wildlifecrossings.info and the Fish Xing website at http://stream.fs.fed.us/fishxing /beta.html.

Designing water conveyance structures as wildlife and fish passages

In areas with high rainfall, roads will have numerous water conveyance structures. Because many animal species use drainages as travel corridors, water conveyance structures are often useful for wildlife passages. Although water goes through these structures, it cannot be assumed they will function as passages for fish or other aquatic organisms. Water conveyance structures such as bridges and culverts can be ideal crossing structures for both aquatic and terrestrial species if they are constructed with the needs of the target species in mind.

The easiest way to determine how to make a water conveyance structure function for wildlife and fish is to simulate a natural stream crossing. "Stream simulation" means that the natural gradient, width and substrate are maintained so that the stream is not fighting with the structure at any flow levels (Clarkin et al. 2005). When stream crossings are constructed with stream simulation in mind, aquatic species will not have to negotiate culverts that are pitched at too great an angle or that have perched outlets. Stream simulation does not address the height of a structure except as it relates to flood events, and usually streams are better simulated as wide crossings rather than as high crossings. Thus, some structures that serve aquatic species very well may not be suitable for wildlife species because they do not have adequate headroom. Wide structures are better than tall and narrow structures for most wildlife species as long as the headroom is adequate (Gordon and Anderson 2003, Foster and Humphrey 1995). A key feature of good stream simulation is that dry areas are maintained along the side of the stream except in flood events, and water is at approximately the same depth as the natural stream (that is, not too shallow and spread out). This allows terrestrial animals, even those very capable of swimming, to travel on dry land instead of wading through water, and aquatic species adequate depth to swim.

Many existing water conveyance structures can be 'retrofitted' to serve aquatic and terrestrial passage. Sometimes this may be as simple as to install a wide shelf (0.5 m) along the edge so that there is a dry surface for terrestrial species to walk. Another example of a useful retrofit is to install sound-moderating surface material in the ceilings of structures to make the sound inside the structures more natural, and therefore less intimidating, to animals (Jacobson, in prep.). Retrofitting existing structures is an emerging field; so many new designs will be developed in the coming years.

Part III. Eco-Logical: An Ecosystem Approach to Developing Infrastructure Projects

Over the last several decades, the understanding of how infrastructure impacts habitat and ecosystems has grown. Consequently, awareness of how to better avoid, minimize, and mitigate impacts has also matured. A new guide has been developed to help agencies form partnerships and translate this awareness into action. Articulating a vision of cost-effective infrastructure development that contributes to ecosystem conservation, *EcoLogical: An Ecosystem Approach to Developing Infrastructure Projects* offers a non-prescriptive approach to making infrastructure more sensitive to wildlife and ecosystems through greater interagency cooperative conservation.

Central to Eco-Logical, which was developed by a steering team of representatives from eight Federal agencies and the Departments of Transportation from four States, is the "ecosystem approach," a method for sustaining or restoring ecological systems and their functions and values. An ecosystem approach is a process for the comprehensive management of land, water, and biotic and abiotic resources that equitably promotes conservation and sustainable use. The goaldriven ecosystem approach in Eco-Logical is based on a collaboratively developed vision of desired future conditions that integrates ecological, economic, and social factors. It is applied within a geographic framework defined primarily by ecological, rather than political or other boundaries.

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To help achieve the approach, the guide offers the conceptual groundwork for integrated planning, a process by which agencies and their partners:

- *Combine planning efforts* – Management plans that agencies and partners have developed individually are important sources of information in the integrated planning process. Some examples of plans include: long-range transportation plans; watershed plans; species recovery plans; resource management plans; state wildlife action plans, forest management plans; Special Area Management Plans; coastal management plans; and community growth plans.
- *Understand where planned infrastructure projects and resources (natural, historic, and cultural) will interact* – Maps from infrastructure and conservation plans can be overlaid to determine the projects and resources that "link" agencies. An overlay of maps can show how planned projects and objectives might cumulatively impact a region's resources, and identify areas where collaboration on project location and design may address multiple and diverse goals within the community and the ecosystem.
- *Define ecological resources of highest concern* – Identification of ecological-priority areas can help ensure that opportunities to protect them through avoidance, minimization, and – if necessary – mitigation are acted upon before critical ecological resources are lost.

Eco-Logical provides a process for the collection, sharing, analysis, and presentation of data in agencies' plans. A key product of this process is a regional ecosystem framework (REF). A REF can help identify ecologically significant areas, potentially impacted resources, regions to avoid, and mitigation opportunities before new projects are initiated. With this understanding, agencies can work together to more accurately identify the areas in most need of protection, better predict and assess cumulative resource impacts, and streamline infrastructure development through increased predictability. Although there is no standard for creating a REF, *Eco-Logical* recommends that a REF consist of an "overlay" of maps of agencies individual plans, accompanied by descriptions of conservation goals in the defined region(s).

Eco-Logical also supports the consideration of ecosystem-based mitigation where appropriate. Ecosystem-based mitigation is the process of restoring, creating, enhancing, and preserving habitat and other ecosystem features in areas where environmental needs and the potential environmental contributions are greatest. It is implemented in conjunction with, or in advance of, infrastructure projects. Ecosystem-based mitigation extends existing compensatory mitigation options by offering a way to evaluate alternatives for off-site mitigation and/or out-of-kind mitigation in the ecologically most important areas as defined by interagency partners and the public. It is a potentially enhanced approach to crediting mitigation that builds on existing approaches. Integrating this new concept with lessons learned from previous experience can allow agencies to capitalize on opportunities for substantial habitat connectivity and wildlife conservation while developing needed infrastructure.

Moving beyond the customary project-by-project approach to meeting infrastructure needs and toward the ecosystem approach defined in *Eco-Logical* can result in a range of benefits, including:

- **Safer, improved infrastructure –** All agencies and stakeholders contribute to the delivery of infrastructure. The collective abilities and knowledge shared in the ecosystem approach should allow a more balanced understanding of ecological and social concerns.
- **Improved watershed and ecosystem health –** Integrating the preventive, diagnostic, and prognostic aspects of ecosystem management should lead to greater understanding of the relationships between ecological issues and human activities.
- **Increased connectivity and conservation –** Since the ecosystem approach takes a broad view that encompasses the interaction of human and natural systems, it can help agencies plan and design infrastructure in ways that minimize habitat fragmentation and protect larger scale, multi-resource ecosystems.
- **Efficient project development –** Uncertainty during project development imposes a high cost on agencies and partners, in both time and money. An ecosystem approach fosters cost-effective environmental solutions that can be incorporated early in the planning and design of infrastructure projects.
- **Increased transparency –** Infrastructure projects developed with an ecosystem approach provide opportunities for, and encourage, public and stakeholder involvement at all key stages of planning and development.

Eco-Logical is available on the Internet at www.environment.fhwa.dot.gov/ecological/eco_index.asp, and in hardcopy by contacting Carol Adkins at (202) 366-2054 or carol.adkins@fhwa.dot.gov.

Tools for professionals

An important aspect of road ecology is the need to bring together interdisciplinary groups of scientists and professionals to develop the science from several disciplines to work together in new ways and develop innovative approaches to the road and natural systems interface. This leads to development of interagency tools and processes that help professionals from various federal, state and local agencies work together despite differing missions and perspectives.

The Federal Highway Administration (FHWA), the agency responsible for transportation planning and project development nationwide, has developed many products that support environmental stewardship in transportation provision. There is an extensive website of their products that includes guidance for wetlands mitigation, context sensitive solutions and integrated planning best practices. By funding research and development of tools and best practices, the federal agency is promoting understanding of the impacts of roads on the natural environment and awareness among transportation engineers and planners that this is a consideration to be incorporated in their work. The FHWA webpage for environmental streamlining and stewardship is a wealth of information and can be found at: http://www.environment.fhwa.dot.gov/strmlng/ndex.asp

Context sensitive solutions

Context sensitive solutions is an important initiative of the FHWA. It is a process for developing transportation projects within the environmental and social context of the surrounding natural environment and the community. Road projects are undertaken with the involvement of the communities surrounding the project and inclusion of the ecological data of the area. Project design is based on the full consideration of community input and environmental conditions such as water, soils, erosion, wildlife and aquatic habitat, cultural and historical resources. Context sensitive solutions is changing the approach to project delivery by training engineers and planners in this approach. The science of road ecology can be an important input to this process. More information about context sensitive solutions is can be found at http://www.fhwa.dot.gov/csd/index.cfm

Integrated planning approaches

Transportation planning is evolving toward a multi-disciplinary, multi-agency practice that includes consideration of road ecology, sharing of environmental data among agencies, setting up processes where coordination can occur and integrating the various plans in a given region and ecosystem. Plans may include the long-range transportation infrastructure plan, habitat conservation plans, local land use plans for accommodating population growth and economic development plans.

This approach moves the focus from the project-level to the landscape level so that all the natural systems and the transportation network can be studied as an integrated whole. This can help agencies collaborate at the regional level and consider a number of planned projects together rather than piecemeal. This can allow more innovative and long-term solutions. It also can allow planners to put together larger areas for mitigating environmental impacts of transportation projects and create higher quality habitat.

Some areas where collaboration and integration of planning processes include: regional integrated watershed management plans that enable small water agencies in an area to work together to manage an entire watershed more effectively and protect it from growth, state wildlife action plans that identify wildlife species for protection and measures each state will take for protection and conservation plans for preserving large land areas from urbanization. One good example is the State of Florida Department of Transportation Efficient Transportation Decision Making Process (ETDM) that provides a large GIS database of environmental resources and land use data for use in a collaborative transportation planning process that also streamlines the environmental permitting required for delivery of projects.

Part IV. Road Ecology Research and Education

University Centers provide focus for collaboration of scientists

In the United States, there are three university centers with a focus on transportation and the environment. The university center is a model and a key driving force in establishing road ecology as a focus for research and policy development. The three centers and their specific areas of activity are listed below.

Center for Transportation and the Environment (CTE), North Carolina State University, Raleigh, North Carolina, focuses on education and training in transportation and the environment. CTE hosts an excellent speaker series bringing expert panels on transportation and the environment to professionals via web-cast. CTE also organizes the International conference on the Environment and Transportation (ICOET), every two years which brings international experts together to present the latest research and best practices to professionals in transportation and the environment. Opportunities for distance learning through CTE can be found at http://www.itre.ncsu.edu/CTE/index.asp.

Western Institute of Technology (WTI), Montana State University, Bozeman, Montana, conducts research on a wide range of transportation topics, including road ecology. The focus in road ecology research is on wildlife crossing and animal-vehicle interactions. WTI can be found at http://www.coe.montana.edu/wti/.

The UC Davis Road Ecology Center (REC), University of California, Davis, California, fosters a synergistic approach to solving road ecology problems, facilitating collaborative projects among scientists, policy makers, transportation planners and engineers. The REC has been successful in elevating awareness of key issues among academic researchers and professionals through research and educational workshops. The Center also works with federal, state and local government agencies to identify scientific and applied research needed by policy makers and professionals in transportation and the environment. This enables the identification of high-priority research directions. The REC can be found at http://road ecology.ucdavis.edu/.

Interdisciplinary road ecology research needs assessments

Some of the challenges to successfully integrating the disciplines of ecology and transportation lie in lack of scientific basis for policies and practices that help transportation agencies meet goals of environmental protection. The Road Ecology Center has developed a research needs assessment workshop approach to identifying focus areas for agencies responsible for transportation and resource protection. The workshop provides a small-group forum to discuss common challenges and barriers to environmental protection in transportation project delivery. This interactive approach to research needs assessment enables the university to respond effectively to current, real-world needs of those agencies responsible for environmental protection and providing transportation infrastructure in a way that could not otherwise occur.

Road ecology education

The first-ever graduate course in road ecology is planned for Spring 2007, to include experiential learning opportunities that allow students from ecology, engineering and social sciences to work together with agencies on real-world problems in transportation and ecology, again emphasizing both the inter- disciplinary nature and the interactive aspects of road ecology research.

In addition to university academic education, the Road Ecology Center, as well as CTE and WTI, provide education for transport- ation professionals who put road ecology science into practice to address problems in the delivery of transportation projects. Technology transfer workshops are organized to engage the professional community in developing the science of road ecology as well as applying it in their practice. Summaries and presentations from REC workshops are posted on the Center's website at: http://roadecology.ucdavis.edu/events.html

Road Ecology Center Visiting Scholars Visiting scholars at UC Davis work on projects of high international interest and relevance. The REC continues to expand partnerships among Pacific Rim universities and transportation officials.

Part V. International Conference on Ecology and Transportation

The International Conference on Ecology and Transportation, or ICOET, is an international gathering of scholars and professionals to share the latest research findings that integrate ecological awareness and best practices with transportation projects, to create sustainable transportation systems. The ICOET meetings are held every two years and are organized by the Center for Transportation and the Environment (North Carolina State University). The next meeting will be held in May 2007 in Little Rock, Arkansas. Proceedings of the past conferences are found on the ICOET website at http://www.icoet.net/index.asp.

Conclusion

Addressing road networks and natural systems in an integrated fashion is a complex contemporary issue. Solutions are urgently needed in the face of rapid economic growth and urbanization. The science of road ecology is a promising new multi-disciplinary field that is being developed to address the range of engineering, planning and ecological solutions to problems such as fragmentation of wildlife habitat, soil erosion and sedimentation caused by roads, roadside plant communities and re-vegetation with native species, wetlands restoration, and storm water run-off and water quality impacts. Scientific research in turn leads to innovative tools for practitioners in transportation departments and resources protection agencies. Such scientific and cost-effectiveness analyses are needed by policy-makers to achieve sustainable transportation systems.

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Modeling the Relationships Between Benthos and Stream Environmental Variables

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Abstract

This study investigated the quantitative relationships between benthic macroinvertebrates and stream environmental variables using generalized additive models. The benthic data used in the study were collected by the Virginia Department of Environmental Quality from 1994 through 2001. The benthic macroinvertebrate assemblages were represented by five benthic metrics namely taxonomic richness, proportion of the two most dominant taxa, proportion of sensitive taxa, proportion of tolerant taxon, and proportion of shredders. Twenty environmental variables, of which eight were physicochemical and twelve were habitat related, represented stream environmental conditions. The study findings suggest a sharp decline in taxonomic richness at total suspended solids concentration of 9 mg/L to 17 mg/L. At flow rates above 85 cfs, taxonomic richness decreases with increasing flow rate. As the dissolved oxygen concentration increases, the proportion of sensitive taxa also increases, while the proportion of tolerant taxon and the two most dominant taxa decreases. None of the physicochemical variables showed a significant effect on the proportion of shredders. Also, the variations of pH within the pH range observed in the case study streams (pH 6 to pH 10) had no significant effects on the responses of the benthic metrics. For the habitat variables, taxonomic richness and sensitive taxa positively correlated with channel flow status and substrate, respectively. Tolerant taxon negatively correlated with substrate.

Keywords: Stream Environmental; Benthos; macroinvertebrate;

J. of Ecotechnology, 2006 (2) : pp.48-65

水底生物與河流環境因子相關模式之探討

本研究對水底大型無脊椎動物（Macroinvertebrates 或 MI）與河流環境因子間量化性之關係作一探討。因 MI 常用為河川生態狀況之重要指標，故此種量化性之關係，可用來做改善環境因子（如流量及水質參數）之根據。

本研究所用之數據為維吉尼亞州環境品質局於 1994 年至 2001 年所收集之資料，MI 族群之分類指標為物種之數量及多樣性、數量最多之二個物種、最敏感物種之比例，以及最抗污染物種之比例。考慮之溪流環境因子共有 20 個，其中 8 個為物理及化學方面之因子，其他 12 個則與棲息地有關。

研究結果顯示在溪流中懸浮固體（TSS）濃度從 9 mg/l 升高到 17 mg/l 時，MI 物種之數量及多樣性有顯著的減少，流量到 85 CFS 以上時亦有相同之情形。在溶氧量增加時，最敏感物種之比例亦隨之增加，而最抗污物種及數量最多之二個物種之比例則相對減少。另外，所用之數據之 pH 值在 6 至 9 之間，對 MI 似無任何影響。在棲地因子方面，MI 族群數量及多樣性，以及最敏感物種之比例，都與流量及河床介質有正面之相關關係，而最抗污物種比例則與河床介質呈負面之相關關係。

關鍵詞：溪流環境，水底生物，大型無脊椎動物，統計模式分析

Introduction

Over the past decades, water resources managers and the public have embraced the use of benthic metrics to supplement physico-chemical analysis in monitoring and assessment of stream environmental conditions. Changes in benthic metrics are predictable when environmental equilibrium is upset due to environmental stressors such as habitat degradation or pollution (Barbour et al., 1999). Generally, assessment of benthos in an impaired stream reach is conducted and the information obtained is used to compute benthic metrics. Also, water quality analyses are carried out, along with evaluation of physical stream habitat features. The results of the assessment are compared to benthic metrics, water quality and habitat condition at a reference site. The reference site needs to have characteristics (location, elevation, geology and hydrology) similar to the waterbody being evaluated, and should support a viable, diverse benthic macroinvertebrate community (Barbour et al., 1999). Limitations in use of reference sites to identify and evaluate the level of impairment in a target stream have been pointed out in the literature. Gergel et al. (2002) have observed that identification of reference sites can be a challenge, especially for large rivers. Walker et al. (2002) point out that it is virtually impossible to select a comparable reference site that exactly matches the characteristics of the target stream. They especially note that reference sites are often different from the target stream in terms of watershed sizes, physical characteristics, flow rates and the natural water chemistry. Furthermore, in some cases a selected reference site is a minimally-impaired site or least-disturbed site due to lack of a non-impaired stream in the area (Plotnikoff and Wiseman, 2001). A minimally-disturbed site is a site that has experienced very little historical human activity that alters stream integrity (Wiseman, 2003). A least-disturbed site is a site that has been degraded by previous human activities, but exhibits some level of recovery (Wiseman, 2003). It could be argued that the minimally- or least-disturbed sites do not provide adequate representation of biotic integrity in an undisturbed site.

In an attempt to provide an alternative to use of reference sites, this study carried out generalized additive modeling (GAM), which is described by Hastie and Tibshirani (1990), to investigate the quantitative relationships between benthic macroinvertebrates and stream environmental variables. The environmental variables investigated comprised eight physicochemical variables and twelve habitat variables. The benthic macroinvertebrate assemblages were represented by five benthic metrics namely; taxonomic richness, proportion of the two most dominant taxa, proportion of sensitive taxa (Ephemeroptera, Plecoptera and Trichoptera), proportion of tolerant taxon (Chironomidae), and proportion of shredders. According to Barbour et al. (1999), taxonomic richness decreases with a decrease in water quality and/or habitat degradation as the less tolerant species are eliminated. The proportion of two most dominant taxa is a tolerance metric that measures the dominance of the two most abundant taxa. A community with a high proportion of dominant taxon indicates that the community is under the influence of environmental stress (Plafkin et al., 1989). The metric referred to as proportion of sensitive taxa represents aquatic insects that are intolerant of pollution and other environmental stressors. Thus, the metric usually decreases with increasing environmental stress. The proportion of tolerant taxon metric increases with increasing pollution and environmental stress. Shredders are sensitive to riparian zone impacts; therefore the proportion of shredders increases as the riparian vegetation zone width increases.

Methods Data sources and acquisition methods

The benthic data used in this study were collected by the Virginia Department of Environmental Quality (VDEQ) from 164 benthic sampling sites (Figure. 1) in 1st through 4th order streams located throughout western Virginia, from 1994 through 2001. The benthic sampling sites span five ecoregions namely the North Piedmont, the Blue Ridge Mountains, the Central Appalachian, the Piedmont, and the Central Appalachian Ridges and Valley. The VDEQ used the U.S. EPA rapid bioassessment protocols (Barbour et al., 1999) for these biological stream surveys, and sampling was carried out twice per year (spring and autumn). However, not all benthic sampling sites were sampled every year from 1994 through 2001. Therefore, the benthic data consist of 839 observations instead of 2624. The VDEQ stores these data in a data management system called Ecological Data Application System (EDAS) (TetraTech, 1999), developed for use with Microsoft Access®. The EDAS database was used to obtain information on the benthic metrics that were selected to illustrate changes in benthic macroinvertebrate assemblages along environmental gradients.

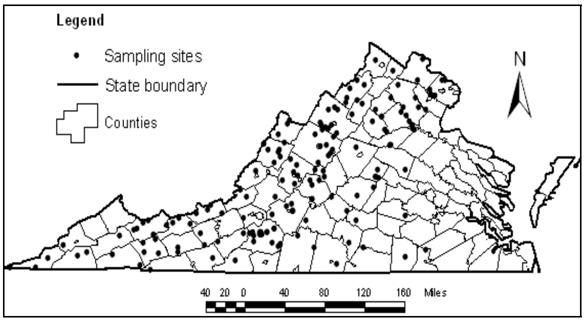


Figure 1. Location of benthic sampling sites in Virginia, U.S.A.

The physicochemical variables that were investigated are total suspended solids (TSS), total phosphorus (TP), nitrate (NO3), dissolved oxygen (DO), water temperature, electrical conductivity, pH, and flow rate. Data on instantaneous measurements of DO, water temperature, electrical conductivity, and pH were available in the EDAS database (TetraTech, 1999). These measurements were taken at the time when benthic sampling was carried out. Data for TSS, NO3, and TP were obtained from the VDEQ website of surface water monitoring program. These data were collected around the time period that the benthic sampling was conducted.

Some benthic sampling sites are located in gauged streams. Therefore, stream flow data for these sampling sites were obtained from the National Water Information System (NWIS) online database of U.S. Geological Survey (USGS). Synthetic flow series were generated for the benthic sampling sites that had no stream flow data using the Drainage-area-ratio (DAR) method (Hirsch, 1979). The DAR method relies on the assumption that the ratio of flows at the outlet of two nearby watersheds is equal to the ratio of the drainage areas of the two watersheds. The equation for estimating the synthetic flow series is expressed as (Equation 1):

$$y_i = \left(A_y \middle/ A_x \right) x_i \qquad [1]$$

where yi is the estimated ith flow at the ungauged site, Ay is the drainage area at the ungauged site, Ax is the drainage area at the gauged site, and xi is the ith observed flow at the gauged site. The procedure for generating the synthetic flow series for a target benthic sampling site involved identification of a gauged site that is close to the benthic sampling site. This was achieved by entering location information (latitude, longitude and name of county) of the target benthic sampling site into NWIS database, which then generated all gauged sites close to the target site. The location of the benthic sampling site and all the adjacent gauged sites were then mapped using ArcView version 8.3 (ESRI, 2002), which allowed visual assessment of proximity of the gauged sites to the benthic site. The gauged site that was closest to the benthic sampling site was selected for generating the synthetic flow series.

Habitat assessment data for each benthic sampling site were provided in the EDAS database (TetraTech, 1999). These data were obtained through visual assessment of habitat features at the time of benthic sampling. Twelve features of physical habitat were rated on a scale of 1 to 20, in which 20 corresponds to highest quality of the habitat feature being assessed. The habitat features assessed were: 1) bank stability, 2) bank vegetative protection, 3) channel alteration due to man-induced activities, 4) channel flow status, 5) embeddedness of stream, 6) epifaunal substrate, 7) grazing or other bank disruptive pressure, 8) in-stream cover, 9) frequency of riffles, 10) riparian vegetation zone width, 11) sediment deposition in stream, and 12) velocity-depth regimes of stream.

Statistical analysis

The Kruskal-Wallis test, a non-parametric ANOVA, was used to examine the variation in benthic macroinvertebrate assemblages in order to determine if it was appropriate to analyze the benthic data collectively. The test was specifically carried out for the following reasons: 1) Since the benthic data used in this study were collected during the spring and autumn seasons, the observed variability in the benthic macroinvertebrate community structure could have been due to seasonal variations and not anthropogenic activities such as pollution or stream habitat degradation; 2) The fact that the benthic sampling sites are located across four different stream orders, the observed variation in benthic macroinvertebrate assemblages may be caused by natural variation of stream conditions as it flows from head- waters to downstream reaches; 3) Since the benthic sampling sites span five ecoregions, there is a possibility that the observed variability in the diversity of the organisms is caused by geographic classification.

Principal component analysis (PCA) was performed on the eight physicochemical variables and twelve habitat variables. The analysis was performed due to the fact that it is common for environmental variables to be significantly correlated. Therefore, there was a chance that some environmental (predictor) variables would be redundant if all twenty variables were included in the development of the benthos-environment relationships. Accordingly, the predictor variables were reduced to a smaller number without losing too much information. This approach of dimension reduction is a common practice in quantitative ecology (Legendre and Legendre, 1998).

Development of benthos-environmental variables relationships

Generalized additive modeling (Hastie and Tibshirani, 1990) is a non-parametric regression technique, which is data-driven rather than model-driven. That is, in contrast to some analytical procedures (e.g., ordination and linear regression models), generalized additive modeling does not make a priori assumptions about underlying relationships, thus allowing the data to determine the fit of the model instead of the model determining the acceptability of the data. Because of the non-parametric nature of GAM, there are no associated regression equations. In order to improve the distributional characteristics of regression residuals of GAM, the taxonomic richness metric was logarithmic transformed while the proportional abundance metrics were arcsine-square root transformed. Distribution of total suspended solids data was strongly skewed therefore this variable was log transformed. The five benthic metrics were regressed against the physicochemical and habitat variables to reveal the relationships between the metrics and the predictor variables. The significance of a predictor variable in a generalized additive model was assessed using model deviance. The deviance for a fitted model is defined as

$$D = -2 \ln [L_c / L_s] \qquad [2]$$

where Lc is the likelihood of the current model, and Ls is the likelihood of the saturated model. A saturated model uses the observed data as fitted values and therefore ascribes all of the variation in data. Generally, deviance plays the role of the residual sum of squares for generalized models, and is used to compare models (Hastie and Tibshirani, 1990). For each smoothing function in a given model, a $\chi 2$-test was performed to compare the deviance between a model with a predictor variable xj and the model without the predictor variable. A predictor variable xj was deemed to have a regression effect if $p < 0.05$ (Xiang, 2001). The partial residual diagnostic plots of the generalized additive models of benthic metrics versus environmental variables were examined to determine how responses of the benthic metrics change along gradients of environmental variables.

Due to a lack of sufficient field data for evaluating the developed models of benthos-environment relationships, the robustness of the models was evaluated using the bootstrap method (Efron and Tibshirani, 1991). The bootstrap algorithm was run and created 100 bootstrap samples. Then generalized additive modeling was performed on the 100 bootstrap samples to examine if the benthos- environment trends in these bootstrap samples were similar to the trends that had been developed using field data.

Results Statistical analysis

Table 1 shows the results of Kruskal-Wallis test on the variability of benthic macroinvertebrate assemblages between spring and autumn seasons, among the five ecoregions, and among the four stream orders. Benthic macroinvertebrate assemblages did not vary significantly ($p>0.05$) among the five ecoregions. Similarly, there were no significant differences ($p>0.05$) in benthic macroinvertebrate assemblages between spring and autumn seasons. Significant differences ($p<0.01$) among benthic macroinvertebrate assemblages were indicated among the four stream orders in which the benthic sampling sites were located. Therefore, it was deemed inappropriate to analyze collectively the benthic data collected from different stream orders because of the confounding effects of variations in stream order. The benthic data were then divided into subsets, in which each subset comprised of data collected from one stream order. Subsequent statistical analyses were restricted to data collected from one stream order, which served as a typical case. In this case, the third order streams were selected, and the data pertinent to this stream order consisted of 280 observations from 52 sampling sites.

Table 1. Results of Kruskal-Wallis Test: p-values on the variability of benthic macroinvertebrate assemblages between spring and autumn seasons, among the five ecoregions, and among four stream orders.

	Taxonomic richness	Proportion of two most dominant taxa	Proportion of sensitive taxa	Proportion of tolerant taxon	Proportion of shredders
Seasons	0.41	0.29	0.08	0.36	0.77
Ecoregions	0.20	0.09	0.28	0.41	0.09

Order	0.00	0.01	0.00	0.01	0.00

For the physicochemical variables, results of PCA revealed that the first four principal components sufficiently represented the variability in the physicochemical data. These four components were retained according to the broken-stick cut-off criterion (Legendre and Legendre, 1998). That is, the individual variances of the first four principal components exceeded those of their broken-stick model counterparts. The four components accounted for approximately 83% of the total variation in the physicochemical variables. The first principal component accounted for 34% of the variation in the data set, the second component accounted for 22% of the remaining variation, and the third and fourth components accounted for 16% and 11% of the remaining variation, respectively. Table 2 shows how the variables loaded on the principal components.

Table 2. Rotated principal components of physicochemical variables

Variable	Component			
	1	2	3	4
TSS	**0.96**			
NO_3	**0.95**			
TP	**0.78**			
DO		**-0.87**		
Temperature		**0.86**		
Flow rate			**0.93**	
Conductivity	0.37		**-0.71**	0.32
PH				**0.97**

Note: Only loadings above 0.3 are displayed.

For the twelve habitat variables, results of PCA indicated that the first three principal components sufficiently represented variability in the habitat features. These three components explained approximately 68.4% of the variation in the habitat variables. Table 3 shows the loadings of the components.

Table 3. Rotated principal components of habitat variables

	Component		
	1	2	3
Epifaunal substrate (benthic macroinvertebrate)	**0.91**		
Riffle frequency of stream	**0.84**		
Embeddedness of stream	**0.83**		
In-stream cover	**0.79**		-0.31
Velocity-depth regimes of stream	**0.78**		
Sediment deposition in stream	**0.68**	0.45	
Riparian vegetation zone width		**0.88**	
Bank vegetative protection		**0.75**	
Channel alteration due to man-induced activities		**0.75**	
Bank stability	0.42	**0.61**	0.36
Grazing or other bank disruptive pressure		**0.59**	
Channel flow status	0.30		**0.95**

Note: Only loadings above 0.3 are displayed

Variables that had the greatest amount of axis loading in PCA (i.e., TSS, DO, flow rate, and pH for physiochemical variables, and epifaunal substrate, riparian vegetation zone width and channel flow status for habitat variables) were selected to represent suites of covarying variables in the subsequent statistical analyses. Spearman's correlation coefficients of the selected environmental variables are shown in Table 4. The small correlation coefficients (r<0.25) indicate that the variables are independent.

Table 4. Correlation table (r-values) of the selected environmental variables

	TSS	DO	pH	Flow rate	Substrate	*RVZW	**CFS
TSS	1.00	-0.01	0.06	0.07	-0.19	0.02	0.09
DO		1.00	0.07	0.04	-0.07	-0.08	0.01
PH			1.00	-0.16	0.11	-0.17	-0.05
Flow rate				1.00	-0.13	0.06	0.20
Substrate					1.00	0.17	-0.09
* RVZW						1.00	-0.05
** CFS							1.00

*RVZW = riparian vegetation zone width; **CFS = channel flow status

Table 5. Physicochemical and habitat variables that have significant association with benthic metrics. Blank spaces indicate that the variable is not significant at $p < 0.05$

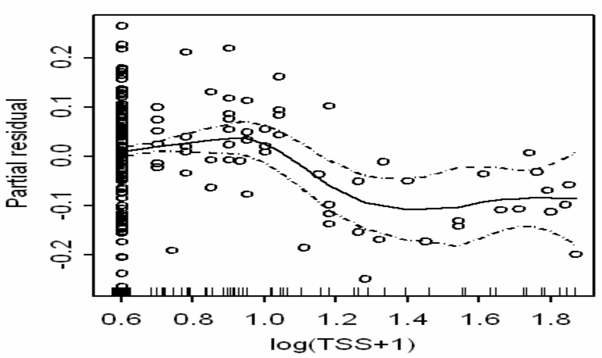
Metric	Physicochemical variables				Habitat variables		
	TSS	DO	pH	Flow rate	Substrate	* RVZW	**CFS
Taxonomic richness	< 0.001			< 0.05			< 0.01
Proportion of two-most dominant taxa		< 0.01					
Proportion of sensitive taxa		< 0.001			< 0.001		
Proportion of tolerant taxon		< 0.05			< 0.01		
Proportion of shredders						< 0.05	

*RVZW = riparian vegetation zone width; **CFS = channel flow status

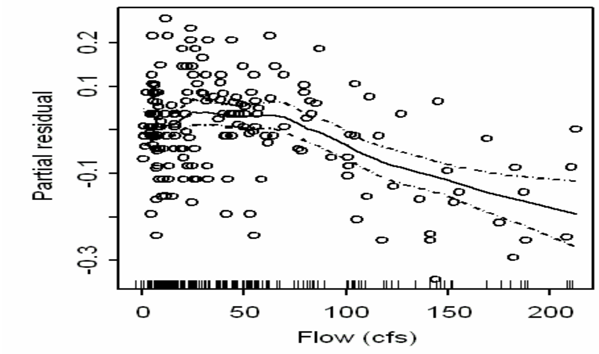
Benthos-environmental variables relationships

The results of generalized additive modeling indicated that not all benthic metrics are significantly associated with the environmental variables (Table 5).

Figures 2A and 2B show the gradient of taxonomic richness versus TSS and flow rate, respectively. Figure 2A shows that taxonomic richness is negatively correlated at high concentrations of TSS. The partial residual values in Fig. 2A seem to line up along log(TSS+1) = 0.6. This is because the minimum detection limit of the method that was used to analyze TSS is 3 mg/L. Therefore, all observations below this TSS concentrations were reported as 3 mg/L. Figure 2B shows that taxonomic richness positively correlates with flow rates less than 25 cfs, then becomes uniform over flow rates of 25 cfs to approximately 85 cfs. At flow rates above 85 cfs, taxonomic richness decreases with increasing flow rate.



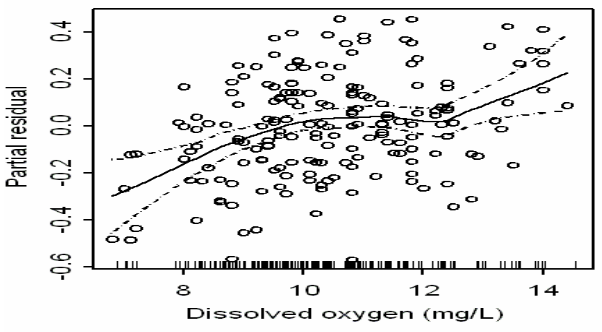
2-A



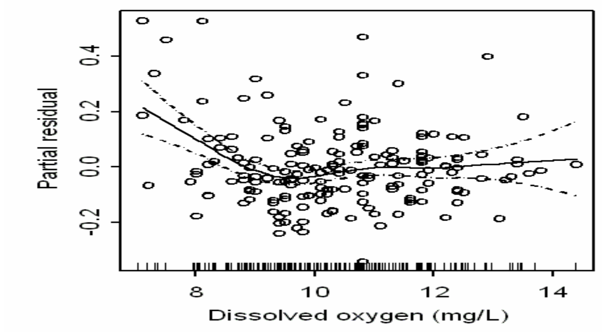
2-B

Figure. 2. Partial residual values and GAM fit for (2-A) taxonomic richness versus log(TSS+1), (2-B) taxonomic richness versus flow rate. The 95% confidence limits are shown as dotted lines.

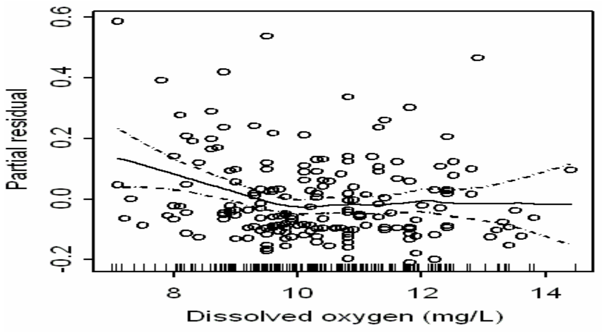
Figure 3 shows changes in the proportions of sensitive taxa, the two most dominant taxa and tolerant taxon along the gradient of DO concentration. The proportion of sensitive taxa increased as DO concentration increased (Figure. 3A), while the proportion of tolerant taxon (Figure. 3B) and the proportion of the two most dominant taxa (Figure. 3C) decreased with increasing DO concentrations from 7 mg/L to 10 mg/L, then leveled off. It is noted that although Figures 3B and 3C show similar trends, different types of taxa account for the two metrics represented in the figures. Fig. 3B represents the proportion of the two most dominant taxa in which the taxa often varied from one observation to another, while Fig. 3C represents the proportion of tolerant taxon, which was sometimes accounted for in the two most abundant taxa. The results of generalized additive modeling indicated that the observed range pH range in the case study streams (i.e., pH 6 to 10) did not cause significant changes in the benthic metrics. Also, none of the physico-chemical variables had a significant effect on the proportion of shredders.



3-A



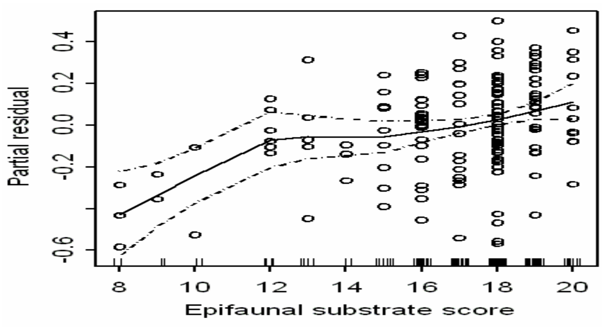
3-B



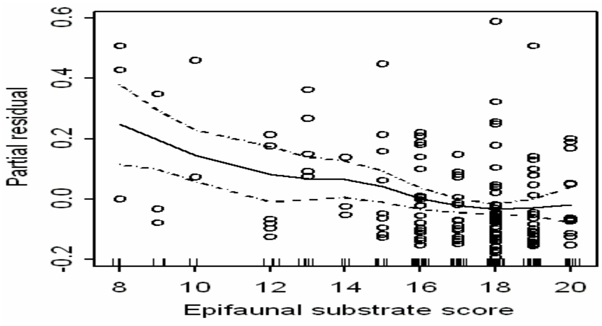
3-C

Figure 3. Partial residual values and GAM fits for (3-A) sensitive taxa, (3-B) dominant taxa, and (3-C) tolerant taxon versus dissolved oxygen. The 95% con- fidence limits are shown as dotted lines.

Figures 4 and 5 show the response of benthic metrics to changes in habitat features. It is notable that partial residual values in these figures are lined up in perfect vertical lines. This is because the scores that describe the quality of habitat features are discrete (rather than continuous) variables. The proportion of sensitive taxa positively correlated with substrate (Figure. 4A), while the proportion of tolerant taxon negatively correlated with substrate (Figure. 4B). Taxonomic richness increased with increasing score of channel flow status (Figure. 5A).



4-A

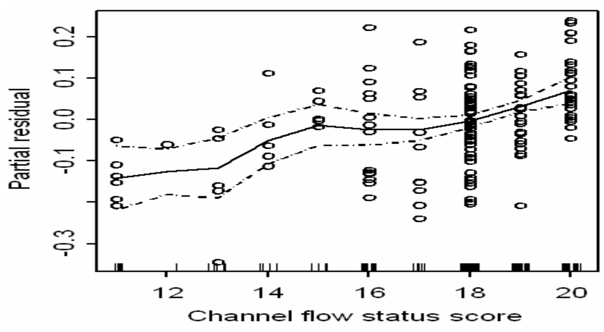


4-B

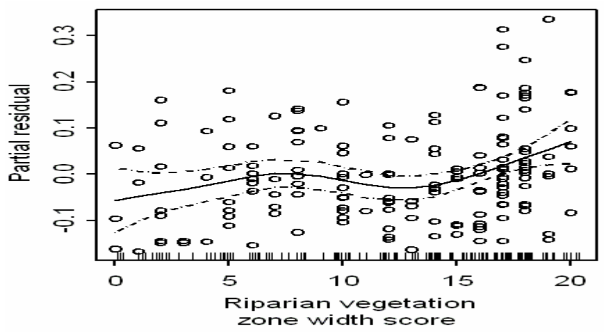
Figure 4. Partial residual values and GAM fits for (4-A) sensitive taxa and (4-B) tolerant taxon versus epifaunal sub-

strate. The 95% confidence limits are shown as dotted lines.

The proportion of shredders increased with increasing score of riparian vegetation zone width (Figure. 5B), except for scores of approximately 9 to 12, there was a decrease in the proportion of shredders. Changes in these three habitat variables had no significant effect on the proportion of the two most dominant taxa.



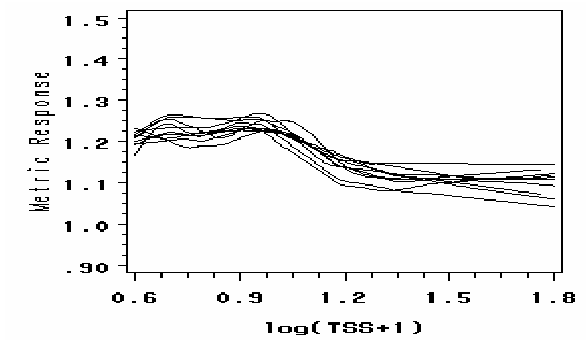
5-A



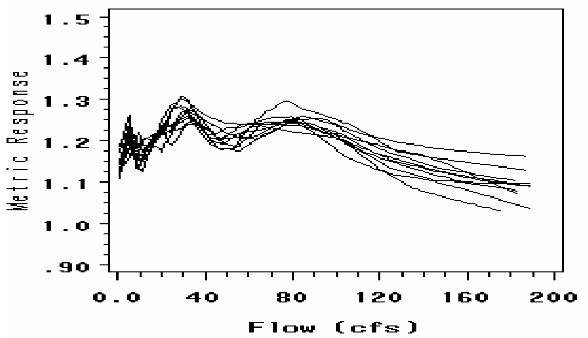
5-B

Figure 5. Partial residual values and GAM fit (5-A) for taxonomic richness versus channel flow status. (5-B) for shredders versus riparian vegetation zone width. The 95% confidence limits are shown as dotted lines.

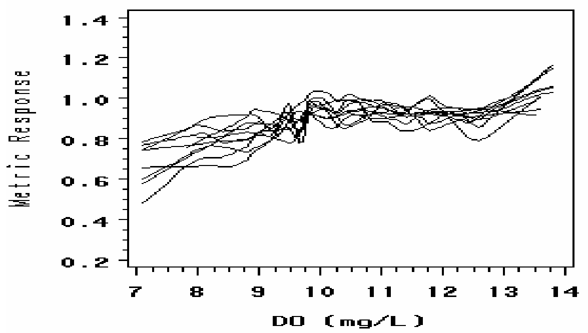
Figures 6A to 6C are typical and representative bootstrap curves generated in the evaluation of the developed benthosenvironment relationships. The bootstrap curves show trends of benthos environment relationships similar to those originally developed, indicative of the robustness of the developed models.



6-A



6-B



6-C

Figure 6. Typical examples of bootstrap GAM curves for taxonomic richness versus (6-A) log(TSS+1) and (6-B) flow rate. (6-C) sensitive taxa versus dissolved oxygen concentration. Only 15 of the 100 bootstrap curves are shown.

Discussion Variability in benthos assemblages

The observed variability in benthic macroinvertebrate assemblages among the four stream orders was probably caused by the same factors as those suggested by Vannote et al. (1980). That is, the variation in composition and structure of benthic macroinvertebrate assemblages along the longitudinal gradient of a river system is linked to shifts in organic matter supply. Thus, the morphological-behavioral adaptations of invertebrates reflect shifts in types and locations of food sources within the stream size, and downstream communities are fashioned to capitalize on upstream organic matter processing inefficiencies (Vannote et al., 1980). The observed low classification strength for the ecoregions supports previous studies conducted in the region (Waite et al., 2000; Yuan and Norton, 2003).

Selection of environmental variables

The rotation of components in PCA allowed better identification of groups of co-varying environmental variables. The components reflect the underlying processes that have created the correlation among the variables (Tabachnick and Fidell, 1996). Therefore, it can be interpreted that the first component reflects a water quality process that involves nutrients and sediment interrelations. The second component suggests an oxygen exchange process in streams, and its dependence on water temperature as indicated by the negative correlation of DO with water temperature. The third component involves the relationship between flow and electrical conductivity. An increase in flow tends to dilute the dissolved salts with a resultant reduction in electrical conductivity. The fourth component suggests acidity properties of streams. With respect to habitat variables, the first component mainly corresponds to habitat features in the stream channel. The second component represents habitat features and activities associated with the surrounding environment of a stream channel. The third rotated component corresponded to features associated with flow processes in the streams.

Benthos-environment relationships

Previous studies have observed that suspended sediments have deleterious effects on benthos (Wohl and Carline, 1996; Wood and Armitage, 1999). However, these studies have not indicated TSS concentrations that cause adverse impacts on benthos. On the other hand, findings of this study suggest that there is a sharp decline of taxonomic richness at TSS concentrations of 9 mg/L to 17 mg/L. It is recognized that the variation in the concentration of suspended sediment and their deposition, is a result of natural variability of stream flow, from high to low flows. For instance, high flows in streams associated with runoff may cause dilution of suspended particulates thereby reducing TSS concentration in a stream. Conversely, high flows can be associated with an increased TSS concentration because of erosion and sediment delivery in a stream. Also, high flows may cause scouring of the streambed, with a consequent increase in TSS concentration. Then again, high flows can widen stream banks, and ultimately reduce flow velocity, which in turn allows settling of sediment. Despite this complex association between TSS and flow rate, it should be noted that this study shows that the decline in taxonomic richness along the TSS gradient is independent of its decline along the gradient of flow rate. This is evident from the lack of significant correlation between TSS and flow rate.

The effects of stream flow on benthos are described in Scheidegger and Bain (1995) and Poff et al. (1997), but the estimates of flow rates that are either too high or too low for benthos are not indicated. Findings from this study indicate that the benthos in the case study streams thrive at flow rates of 25 cfs to 85 cfs (Figure 2B). Nonetheless, it is recognized that velocity is a more direct measure of effects of discharge on benthos than flow rate. For example, a stream may have a high flow rate but low velocity if its cross-sectional area is large. As such, the stream may not exhibit significant effects on benthos. On the other hand, a stream with low flow rate but high velocity may cause significant impacts on benthos as the fast current dislodges the organisms and their habitats.

The observed DO concentrations in the case study streams (i.e., 7 mg/L to 14 mg/L) are at a high end of the spectrum, even for fresh clean waterbodies. This may be a reflection of very good re-aeration mechanisms such as turbulence caused by rapids and horizontal direction changes, in addition to the streams being relatively shallow. The observed decrease in the proportion of the two most dominant taxa and the proportion of tolerant taxon at DO levels above 7 mg/L can be explained by implications of changes in benthic community diversity. It can be argued that high DO concentrations cause an increase in the diversity of benthic macroinvertebrate community, and in turn this reduces the likelihood of a few taxa dominating the community. That is, at higher DO levels the dominant taxa and tolerant taxon lost lose their competitive advantage. In general, an important question here is “Do high dissolved oxygen levels have direct adverse impacts on any taxa, or the impacts are due to competition borne out of other environmental conditions?” This is in view of the fact that when the DO levels are high, conditions are favorable for all aquatic fauna. Therefore, the resulting conditions may enable other non-dominant taxa gain competitive advantage due to their other attributes. Since there are no observations at low DO concentrations, the study could not determine the effects of low DO on benthos. Dauer et al. (1992) observed that characteristics of macroinvertebrate communities in waters having low DO (<2 mg/L), include lower species diversity. The observed insignificant effects of DO on taxonomic richness and the proportion of shredders is probably because these two benthic metrics include several species of benthos, which thrive under different levels of DO concentration. Thus, the adverse response of some individual taxons to changes in DO concentration tends to be offset by positive responses of other taxa, resulting in no noticeable change in the overall metric response to changes in DO concentration.

Figure 4A shows that there is a steep increase in the proportion of sensitive taxa between substrate scores of 8 and 12, and also between scores of approximately 15 and 20. No change is observed between scores of about 12 and 15. The leveling off of proportion of sensitive taxa between scores of about 12 and 15 was probably caused by other factors such as predation, which were not quantified in this study. For example an increase in the proportion of sensitive taxa might have triggered predation by other organisms, consequently inhibiting the increase in sensitive taxa population. However, due to the favorable conditions, the sensitive taxa were able to transcend the impacts of predation and continue to increase as is seen at scores above approximately 15. The proportion of tolerant taxon showed the expected trend at increasing scores of substrate (Figure. 4B). That is, a wide variety and/or abundance of substrate in a stream increased habitat diversity, and this in turn increased species diversity which might have resulted in a decline of the tolerant taxon.

Figure 5A shows taxanomic richness increases as the channel flow status increases. When water covers much of the streambed, the amount of suitable substrate for benthos increases because riffles, cobble, logs, and snags are not exposed (Barbour et al., 1999). Consequently, taxonomic richness increases due to the increased areas of good habitat (Barbour et al., 1999). Shredders are particularly good indicators of toxic effects when the toxicants (e.g., pesticides, herbicides) involved are readily adsorbed to the coarse particulate organic matter (CPOM) such as leaf litter, and either affect microbial communities colonizing the CPOM or the shredders directly (Mandaville, 2002). Logically, as the riparian vegetation zone width increases, more removal of pollutants from runoff takes place due to more retention time attributed to longer flow distance. Specifically, the longer flow distance allows more time for processes such as microstraining and plant uptake of toxicants to take place. However, based on the findings from this study, it is not clear why these processes exhibited significant effectiveness only at scores higher than 12 (Figure. 5B). The observed trend at scores less than 12 was probably caused by other factors that influenced correlation of the proportion of shredders with scores of riparian vegetation zone width. For instance the riparian vegetation may not be able to trap or uptake toxicants in the subsurface flow. Therefore in case streams are located in highly permeable soils, toxicants can reach the streams through the subsurface flow. Consequently, the toxicants impact the shredders. Therefore, in such cases the scores of riparian vegetation zone width might not positively correlate with the proportion of shredders as expected.

Conclusion

Using real-world data, this study has demonstrated that the relationships between benthos and environmental variables can be quantified. The study has identified several attributes in benthic macroinvertebrate assemblages that respond to changes in physico-chemical conditions and habitat features. It has been observed that benthos vary in their response to environmental variables. Taxonomic richness decreased as TSS and flow rate increased. Likewise, the proportion of the two most dominant taxa and proportion of tolerant taxon decreased with increasing DO concentration. On the contrary, the proportion of sensitive taxa increased as the concentration of DO increased. In regard to habitat variables, it was observed that taxonomic richness positively correlated with channel flow status. Also, the proportion of sensitive taxa positively correlated with substrate, while the proportion of tolerant taxon negatively correlated with substrate. Understanding this association between benthos and environmental variables is critical for diagnosing correlates of benthos impairment. This is important mainly because at present the diagnosis process depends on reference sites despite the acknowledged limitation of these sites. The study results are mainly applicable to third order streams in the case study area since the developed models of benthos-environment relationships have been derived using data collected from these streams. However, the developed approach to quantify benthos-environment relationships can be used for other stream orders or regions.

Acknowledgement

This paper is based upon work supported under a Fulbright Scholarship from the Institute of International Education (IIE), U.S.A., and an award from Delta Kappa Gamma Society International (DKGSI), U.S.A., to the senior author Any opinions, findings, or recommendations expressed in this publication are those of the authors and do not reflect the views of IIE or DKGSI. We thank Alex Barron from Virginia Department of Environmental Quality for providing the bio-assessment data.

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