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Bridging the Gap Between BMP Effectiveness and Receiving Water Quality Protection

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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.

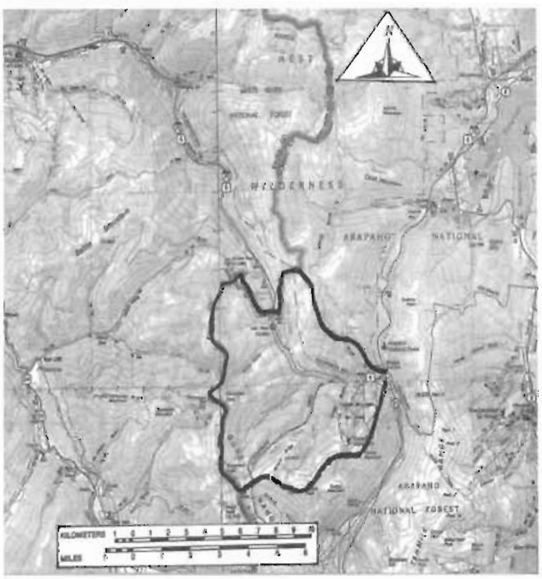

Figure 1. General Location Map and West Tenmile Creek Watershed

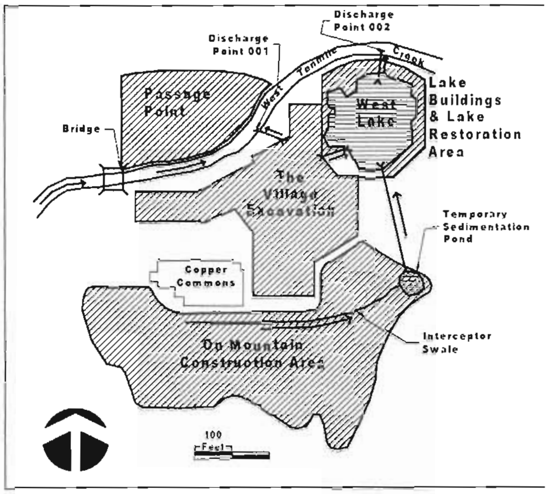

Figure 2. Copper Mountain Base Area Expansion Core

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,

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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 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.

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

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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 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	Conductivity	P, Diss.	DO	Hardness	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	0.02J	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	0.02J	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	0.02J	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	0.02J	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	0.03J	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	0.03J	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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