LAND RECLAMATION AT MUNICIPAL LANDFILL SITES

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Abstract

The recent trend towards closure and reclamation of municipal landfills, and in particular, smaller rural sites, is driven by economic and regulatory requirements. Improved economies of scale associated with larger operations encourage closure of small landfills and centralization of landfilling operations into fewer, larger sites. In addition, the 1993 Ministry of Environment, Lands and Parks "Landfill Criteria for Municipal Solid Waste" has resulted in closure of smaller problem sites rather than the more expensive alternative of upgrading the facilities to meet the new criteria.

Closure of municipal landfills presents a formidable reclamation challenge involving multiple objectives including 1) isolating refuse, 2) minimizing leachate production, 3) preventing erosion, 4) collecting and disposing landfill leachate and landfill gas, 5) returning the land to its original productive state, particularly on lands within the Agricultural Land Reserve, 6) issues associated with application of biosolids as a topsoil amendment and, 7) closure and post closure environmental monitoring to continually ensure that landfill impact on its surroundings are kept at acceptable levels until stabilization or, for approximately 25 years post closure.

This paper draws on Sperling Hansen Associates' (SHA's) recent experience in the design of closure systems for the Hartland Landfill, located 30 km north of Victoria, and the Savona Landfill, located 40 km east of Kamloops, the Squamish Landfill and the Whistler Landfill. To illustrate the key issues associated with implementing practical closure and reclamation of landfills in British Columbia, a detailed case history of the Savona Landfill Closure is presented.

BACKGROUND

Up to the mid 1980's, the majority of landfills across B.C. were sited and operated on somewhat of an "ad hoc" basis. In general, a landfill site was developed to serve each rural community and funded by local taxation. Convenient travel distance for the user population and low lying (out of sight) topography appear to have been the controlling siting factors.

During the mid 1980's, legislation was put in place requiring each Regional District to prepare a Solid Waste Management Plan (SWMP). The primary objectives of the SWMP were to liaise with the public and, based on public opinion and economics, to prepare an organized plan for efficient and environmentally sound solid waste disposal in the future. Not surprisingly, improved economies of scale associated with larger operations favoured closure of the smaller sites and centralization of solid waste disposal into fewer, larger landfills operated on a "user pay" basis (i.e. via tipping fees). The trend to centralize landfilling operations has been further augmented by publication of the Ministry of Environment, Lands and Parks (MoELP) 1993 "Landfill Criteria for Municipal Solid Waste". Guidelines presented within this document encourage closure of smaller sites rather than the more expensive alternative of upgrading the facilities to meet the new environmental protection criteria.

LANDFILL CLOSURE CRITERIA

The 1993 MoELP Landfill Criteria specify that a low permeability and erosion resistant final cover system is to be placed on completed portions of the fill. The cover must comprise at least 1,000 mm of compacted soil with a permeability of less than 1 x 10^{-7} m/s overlain by at least 150 mm of top soil which
incorporates appropriate surface water run-on / run-off drainage controls, is constructed with slopes of between 4 - 33 % and is able to support a healthy vegetative cover. Based on site climate, geology, hydrogeology, leachate and landfill gas management issues, as well as the anticipated end use of the site, components of this conventional closure system may be modified if the proposed alternative performs to an equivalent standard.

Post closure, environmental monitoring should be conducted to continually assess the impact of the site on its surroundings until the waste has stabilized. A post closure period of 25 years is recommended by the MoELP.

**LARGE VERSUS SMALL LANDFILLS**

In B.C., active landfills vary greatly in size. Large sites include the City of Vancouver Landfill in Delta and the Hartland Landfill outside Victoria which accept approximately 440,000 and 150,000 tonnes per year respectively. Moderate sized landfills include the Penticton, Whistler and Squamish Landfills which accept approximately 40,000, 15,000 and 12,000 tonnes per year respectively. Smaller sites include the Heffley Creek Landfill and the recently closed Savona Landfill, both located in the Kamloops area. Heffley Creek currently receives approximately 4,500 tonnes of waste per year. Prior to closure of the site in 1996, approximately 700 tonnes of waste was accepted annually at the Savona Landfill. At the extreme end of the small scale are the unsupervised and generally remote landfills such as the 20 tonne per year Manson Creek Landfill, located on a remote stretch of road between Manson Creek and Germasen Landing, 4 hours north of Fort St. James.

Although site geology and climate are important controlling factors on closure system options, landfill size also plays an important role in the complexity of site closure. At the larger sites, research of closure options, more complex engineered systems and progressive closure are generally implemented due to the higher potential for environmental impact from a larger landfill footprint. In addition, larger sites are more likely to be in a better position to accumulate a substantial portion of tipping revenues collected during landfill operations and to reserve those funds toward final closure. Therefore, larger sites afford installation of more comprehensive closure systems. In contrast, smaller landfill sites generally do not pose as large an environmental risk and are generally financed directly from regional taxation. Complex closure strategies are therefore not often justified and it becomes important to identify and concentrate efforts on the critical closure issue.

**DRY VERSUS WET SITES**

The West Coast of B.C. is characterized by moderate temperatures and precipitation rates in excess of 1,000 mm per year. For example, average annual precipitation rates recorded between 1951 and 1990 at Environment Canada's Victoria (Highland Station), Vancouver Airport, Terrace Airport, Hope Airport and Squamish climate stations are 1,167 mm, 1,138 mm, 1,295 mm, 1,918 mm and 2,247 mm respectively. The combination of moderate temperatures and high precipitation rates results in a high annual water surplus where, the water surplus represents that portion of precipitation which is available for surface water run-off and infiltration (i.e. precipitation minus evapotranspiration). Without controls, a high water surplus means a high leachate generation potential. Design of low permeability closure systems which minimize infiltration, promote run-off and divert run-on, sedimentation ponds and leachate storage lagoons are therefore important components of landfill closure within B.C.’s West Coast wet belt.
In contrast, landfills sited in the interior of B.C., located within the rainshadow of the West Coast Mountains, are typified by more extreme temperatures and by low average annual precipitation rates. For example, average annual precipitation rates recorded between 1951 and 1990 at Environment Canada's Burns Lake, Penticton Airport and Kamloops Airport climate stations are 456 mm, 309 mm and 270 mm respectively. The water surplus and therefore the leachate generation potential is low. However, spring thaws are generally rapid and these sites often experience high intensity short term storm events. Important considerations for landfill closure within this climatic zone include surface water diversion ditching and re-establishment of a healthy vegetative cover.

To illustrate this contrast, Figure 1 presents estimated leachate generation rates (the Thornthwaite and Mather water surplus) versus precipitation for 11 B.C. landfill sites. As is intuitive, the graph indicates a positive relationship between precipitation and leachate generation potential. Based on our experience at over 60 landfills across B.C., a high leachate generation potential can be expected at sites with an annual water surplus in excess of 1,000 mm, a moderate leachate generation potential at sites with a water surplus between 1,000 mm and 250 mm. A low leachate generation potential can be expected at landfills where the average water surplus is below 250 mm per year.

**Figure 1** Relative Leachate Generation Potential at B.C. Landfills

![](image)

**LANDFILL CLOSURE PLANNING**

A landfill closure and reclamation plan involves the following steps: 1) a desk and field investigation program to assess site geometry (i.e. landfill footprint area, refuse thickness etc.), local hydrogeological conditions and available on-site closure materials; 2) design of the landfill final contours; 3) identification of potential capping system options; 4) water budget modelling to determine potential leachate generation rates under different capping system designs; 5) slope stability analysis; 6) selection of the most effective capping system design; 7) design of surface water controls; 8) leachate and gas management plans; 9)
preparation of a reclamation and end-use plan and, 10) preparation of a closure and post closure environmental monitoring plan.

In order to illustrate the key issues associated with implementing practical closure and reclamation of landfills in B.C., we present a case study documenting SHA’s recent experience in the design of closure systems for the Savona Landfill.

**CASE STUDY - CLOSURE OF THE SAVONA LANDFILL**

In accordance with their Solid Waste Management Plan, SHA were retained by the Thompson-Nicola Regional District (TNRD) in June, 1996, to prepare a closure plan for the Savona Landfill to be implemented in the Fall of 1996. The site was to be brought to design grades with additional fill, capped and transfer bins were to be constructed on top of the closed site.

**Physical Setting**

In July, 1996, the landfill footprint covered an area of 0.96 ha within a dry gully, approximately 1 km northwest and overlooking Kamloops Lake and the lake outflow to the Thompson River. The landfill crest, comprising approximately 75% of the total footprint area, was essentially flat. The side slopes were bermed at 2H:1 V, ranging in height from 5 - 15 m and jutting 1 - 3 m above the landfill surface. The western and northern portions of the property remained undisturbed and were vegetated with a naturally sparse stand of native grasses, sage, cacti and occasional ponderosa pine. The topography rises steeply to the north of the site. A fenced cutbank which rises above Highway #1, forms the southern boundary of the site. Based on historic information, waste thicknesses vary from 5 - 15 m across the site from north south.

**Climate**

Savona is characterized by mild winters and hot summers. Data collected at the Kamloops Airport Climate Station (located 38 km east of the site), suggests a very low mean annual precipitation of approximately 270 mm. Annual evapotranspiration, estimated at 222 mm using the Thornthwaite Method, indicates a minimal annual water surplus of only 48 mm.

**Geology**

The geology underlying the site comprises at least 50 m of gravel, gravely sand and sand. Grain size analysis indicates that the exposed material comprises approximately 60 % gravel and 40 % sand. Based on grain size distribution, the hydraulic conductivity of this material is likely to range between $1 \times 10^{-4}$ m/s to $1 \times 10^{-2}$ m/s. If screened to a sand grade and mixed with an organic amendment, SHA noted that the on site soils could be used to construct the topsoil layer of the final cover. Insufficient low permeability materials for construction of a final cover barrier layer were observed on site.

However, due to the very dry climate experienced in this area, SHA recognized that installation of a 1 m thick low permeability final cover barrier layer, as specified by the MoELP Landfill Criteria, may provide no added benefit in terms of reduction of leachate generation in comparison to a 1 m thick local sand final cover layer. HELP modelling to compare leachate generation under these two final cover scenarios was therefore conducted as a means of providing technical justification for an exemption for this site from the low permeability cover requirements.
HELP Modelling

The U.S. EPA Hydrologic Evaluation of Landfill Performance (HELP) Model predicts leachate flows through a landfill system based on a water budget analysis and the hydrogeology and geometry of the landfill. To assess leachate generation at the Savona site under current and closed conditions, three different cover scenarios were modeled as listed below and illustrated in Figure 2.

1. an existing 300 mm sand and gravel intermediate cover system;
2. a 1,000 mm thick local sand barrier layer and 150 mm topsoil layer final cover system;
3. a PVC membrane composite final cover system comprising 150 mm sand, 40 mil PVC, 150 mm sand and 150 mm topsoil.

The various hydrologic components considered in the model are illustrated in Figure 3. The results of the HELP Model simulations are presented in Table 3.

Table 3 HELP Model Simulation Results for the Savona Landfill

<table>
<thead>
<tr>
<th>HELPScenario</th>
<th>Cover Description</th>
<th>Areal Leachate Production (mm/yr)</th>
<th>Total Leachate Production (m³/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Existing Intermed. Cover</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leakage through intermed. cover</td>
<td>13</td>
<td>153</td>
</tr>
<tr>
<td></td>
<td>Leakage from base of waste</td>
<td>95</td>
<td>1,117</td>
</tr>
<tr>
<td>2</td>
<td>Proposed Local Sand Final Cover</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leakage through sand final cover</td>
<td>66</td>
<td>779</td>
</tr>
<tr>
<td></td>
<td>Leakage from base of waste</td>
<td>115</td>
<td>1,357</td>
</tr>
<tr>
<td>3</td>
<td>Optional PVC Final Cover</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leakage through PVC membrane</td>
<td>0.8</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>Leakage from base of waste</td>
<td>85</td>
<td>1,003</td>
</tr>
</tbody>
</table>

Note: 1. Existing landfill area with intermediate cover = 0.96 ha
2. Landfill area with final cover = 1.18 ha

The HELP analysis suggests that installation of a 1,000 mm local sand barrier final cover system will increase leakage through the cover system from 13 mm per year to 66 mm per year. The total moisture infiltrating into the refuse is therefore expected to rise minimally from 153 m per year (0.005 l/s) to 779 m per year (0.024 l/s). Although counter intuitive, we interpret that the pervious final cover will allow more water to penetrate below the evaporative zone, thus making it unavailable for subsequent evaporation. Hence a small increase in the rate of leachate production.

As indicated on Table 3, HELP modelling predicts that installation of a PVC geomembrane final cover would reduce moisture infiltration into the refuse from the current 13 mm per year to 0.8 mm per year. Although the amount of moisture infiltrating into the refuse would drop from 153 m³/yr to 9.2 m³/yr, HELP predicts that over the next five years the amount of leachate actually generated would decrease only marginally relative to existing conditions from 1,117 m³/yr (0.035 l/s) to 1,003 m³/yr (0.031 l/s). This is because HELP predicts that the majority of leachate will be derived from water already stored within the refuse.
Figure 2  Cover System Concepts at the Savona Landfill Analyzed with the HELP Model

Figure 3  Hydrologic Components of the U.S. EPA HELP Model at the Savona Landfill
It should be noted that, for all three scenarios modeled for the Savona Landfill, the total volume of leachate predicted to migrate from the refuse is minimal. Table 4 below provides a comparison between the leachate generation rate predicted for Savona with other B.C. municipal landfills.

Table 4  Estimated Total Leachate Production for B.C. Landfills using HELP

<table>
<thead>
<tr>
<th>Landfill Site</th>
<th>Location</th>
<th>Total Leachate Production (m³/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squamish</td>
<td>Squamish, B.C.</td>
<td>121,543</td>
</tr>
<tr>
<td>Hope</td>
<td>Hope, B.C.</td>
<td>28,787</td>
</tr>
<tr>
<td>Whistler</td>
<td>Whistler, B.C.</td>
<td>22,076</td>
</tr>
<tr>
<td>Knockholt</td>
<td>Houston, B.C.</td>
<td>2,654</td>
</tr>
<tr>
<td>Campbell Mountain</td>
<td>Penticton, B.C.</td>
<td>1,830</td>
</tr>
<tr>
<td>Heffley Creek</td>
<td>Heffley Creek, B.C.</td>
<td>1,309</td>
</tr>
<tr>
<td>Savona</td>
<td>Savona, B.C.</td>
<td>1,117</td>
</tr>
</tbody>
</table>

Note: Leachate reduction rate reported is that for existing landfill prior to installation of a final cover system.

In summary, HELP modelling of the Savona Landfill indicated that leachate production prior to closure was very low and would continue to be low regardless of the type of final cover system selected. Since the local sand cover system will result in a leachate production rate only slightly higher than would be the case with a plastic geomembrane (115 mm vs. 85 mm per year), SHA recommended that the on-site sand be used for closure of the site. Our recommendation, later approved by the MoELP, resulted in a cost saving for the Thompson-Nicola Regional District of approximately $250,000.

Final Contours
To determine the optimum final contours for Savona Landfill site, SHA developed a closure concept subject to the following design constraints: 1) the design must conform with the MoELP Closure Criteria; 2) the final topography must blend into the surrounding landscape; 3) the transfer station design developed by the TNRD must be incorporated into the final design and, 4) sufficient quantities of local sand are to provided from on-site resources to cap the final design landfill footprint. The proposed final landfill configuration developed by SHA to meet these objectives is presented on Figure 4 in plan view and in cross section on Figure 5.

SHA proposed that the crest be capped with 1,000 mm of local sand overlain by 150 mm of topsoil. To provide positive drainage, the cover system would be crowned along a central ridge running east-west. The ridge would be achieved by placing additional refuse received at the site and material excavated during smoothing of the outer berms on to the centre of the site.

As illustrated on Figures 4 and 5, the TNRD's transfer station design was incorporated into the final contour design outside the northern edge of the landfill footprint to locate the structure on solid ground and avoid problems associated with waste settlement.
**Borrow Operations**

In order to determine the volumes of cut and fill that would be required to achieve our final design contours, we conducted three dimensional terrain modelling to calculate the volume between the existing and final contour surfaces. Our analysis indicated that approximately 4,500 m$^3$ of soil would have to be excavated to establish flat grades on the upper transfer station pad. Since our final cover system design (150 mm of topsoil overlying 1,000 mm of sand) for the 1.18 ha final design footprint would require approximately 13,500 m$^3$ of local soils, an additional volume of approximately 9,000 m$^3$ of local material would have to be borrowed from an on-site location. As indicated on Figure 4, a borrow area was developed on the west side of the footprint to obtain the material volume required. Photo 1 shows the partially completed landfill closure with the gravel ridge used as a borrow area in the background.

**PHOTO 1**

**Surface Water Controls**

Analysis of representative short term Intensity-Duration-Frequency (IDF) data indicates that the Savona site is likely to experience high intensity storm events occurring over a time frame of less than 30 minutes. Due to the steeply rising topography to the north of the site and the fact that the Savona Landfill has been developed within the base of a dry gully, SHA anticipated that without proper surface water controls runoff could potentially result in washouts and increased leachate generation during these high intensity, short term storm events as surface water flowed downgradient through the site, following its natural course to Kamloops Lake and the Thompson River.

We proposed construction of a run-on diversion ditch on the north side of the landfill footprint to intercept clean run-on from the upslope catchment. A second ditch was proposed on the south side of the transfer station access road to convey water that may accumulate on the landfill surface and bin area. To accommodate anticipated flows, the ditches were designed with side slopes of 2H: 1V and a base width of
500 mm to a depth of 850 mm. A 150 mm layer of 25 to 75x25 mm rip-rap was recommended as protection over the northern ditch surface where the major flows were expected. A typical section through this ditch design is presented on Figure 5. Photo 2 illustrates the completed ditch.

PHOTO 2

Construction
Construction of the final cover barrier, surface water diversion controls and transfer station were completed by the TNRD in October, 1996. SHA's design plan was followed with the exception culverting a portion of the northern diversion system from the east side of the transfer station to the ditch located on the north side of the landfill access road.

1997 Washout
On February 16, 1997, Chinook like conditions caused the approximately 300 mm thick snow pack on the slopes to the north of the landfill to melt rapidly, causing excess run-off and flooding. Inspection of the catchment above the landfill indicated that flows were exacerbated by the failure of a small earth dam that backed up water over a large area of land approximately 500 m northwest of the site. Once the breach was created, the water flowed down over the nearly flat high land to the northwest of the site into the two gullies which, as indicated by the contours on Figure 4, flow southwards and eastwards toward the Savona Landfill site.

As shown in Photo 1, flow from the eastern gully spilled down the newly constructed borrow slope, eroding the bank and depositing the debris on the closed landfill surface in an alluvial fan approximately 300 mm thick. The flow continued over the edge of the landfill onto the steep highway cut, eroding the sand embankment and blocking 2 lanes of the Trans Canada Highway. The resulting washout is depicted
Flow from the northern gully entered the rip-rap lined diversion ditch and was effectively conveyed into the 18 inch culvert from where the water was conducted into the original ditch along the northern side of the landfill access road. Considerable erosion of the ditch downstream of the landfill and partial washout of the blacktop occurred along the north side of the landfill access road, past the outflow of the culvert.

To prevent recurrence of the February 16, 1997, event SHA recommended the following remedial measures be taken: 1) if the upstream dam is rebuilt, it should be properly engineered with a reinforced spillway; 2) the emergency response diversion ditching on the north side of the site should be maintained; 3) the diversion ditching on the south side of the site should be deepened, reinforced with rip-rap and ditch flows should be directed to the north side of the landfill access road through a 16 inch culvert near the landfill entrance gate; 4) the eroded ditch on the north side of the landfill access road should be repaired, rip-rapped should include rock berm sedimentation traps in the ditch at 20 m intervals; 5) a rip-rap armoured spillway should be constructed from the main 18 inch culvert inlet to convey any overflow around the bin area into the north access road ditch in the event that the culvert is overtopped or clogged.

**Topsoil Construction**

Based on our prior knowledge of site hydrogeology and climate, SHA prepared a cost effective study on the use of biosolids as a topsoil amendment for the Savona site as a support document for the TNRD's biosolids permit application. Land-dried biosolids considered in the study were obtained from a stockpile of tertiary treatment plant sludge from the City of Kamloops Waste Water Treatment Plant. Based on metal content, Kamloops biosolids meet the highest metal standard "Retail High Grade" as specified in the 1983 Guidelines for the Disposal of Domestic Sludge and can theoretically be applied at a maximum rate of

*PHOTO 3*

in Photo 3 after the highway was cleaned up. To minimize damage to the highway, emergency response by the highway maintenance contractor involved diverting the flow along the northern perimeter of the site.
the 1983 Guidelines for the Disposal of Domestic Sludge and can theoretically be applied at a maximum rate of 1,333 dry tonnes / ha. At a mixing ratio of 2 parts biosolids to 1 part sand, this would result in a topsoil thickness of up to 580 mm.

With our December, 1996, study as supporting documentation, the TNRD obtained a permit from the MoELP in February, 1997, to apply biosolids as a topsoil amendment at Savona at a rate of 1,200 dry tonnes / ha.

In June, 1997, the TNRD supervised biosolids application to 0.6 ha of the closed footprint to the south of the transfer station. The ground was first prepared by hand picking grains larger than cobble size from the surface. Kamloops WWTP biosolids were trucked to the site, end-dumped and spread to a thickness of approximately 80 - 100 mm over the prepared surface using a small bulldozer. This application rate is equivalent to approximately 1,200 dry tonnes / ha. The biosolids were disced into the 150 mm thick layer of sand topsoil to a depth of about 100 mm and raked to achieve an even surface. The area was cyclone seeded on June 28, 1997 with a Dryland Forage Mix produced by Richardson's Seeds and comprising approximately 40 % crested wheatgrass, 15% intermediate wheatgrass, 15% annual ryegrass, 5% bromegrass and 25% alfalfa. Signs were set up along the perimeter of the treated area to warn the public of the use of biosolids and to request the public to keep off the freshly seeded site.

CONCLUSIONS

Based on our experience in the design and implementation of closure systems at numerous landfills in British Columbia, we draw the following conclusions:

Implementation of closure systems is not cheap. Typical closure costs for cover systems that meet all MoELP Criteria for landfill closure are $20 to $30 per m². At sites with low leachate generation potential, these costs can potentially be reduced by utilizing locally available soils, subject to MoELP approval, as was demonstrated in the Savona Landfill case history.

It is important to establish a detailed closure plan well in advance of closure implementation so that the true costs of closure can be identified long before the landfill is closed and funds for closure can be accumulated. For example, discovering that their closure costs of the Squamish and Whistler Landfills would exceed $1.5 million each forced those two municipalities to extend their landfill lives by several years so that sufficient revenue to pay for closure could be collected.

The window of opportunity for construction of a final cover system on the West Coast is during the summer months between May and September. To avoid halting construction part-way and the additional expense of installing temporary sedimentation control facilities and erosion protection tarps, construction should not be initiated in late summer or early fall unless it is absolutely certain that the project can be completed before the fall rains or winter frosts set in.

Construction of final closure systems requires large amounts of soil, particularly if a 1,000 mm thick clay barrier is selected. The borrow area for these materials must be identified well in advance of construction. To minimize impacts on landfill operations, it is best to stockpile all construction materials on-site before commencement of the closure contracts.
Suitable top soil material is not available at many operating landfill sites. In areas deficient in organic soils, good top soil can be created by importing biosolids from municipal waste water treatment plants and mixing the biosolids with on-site mineral soils. At new sites, we recommend stripping and stock piling the top soil for ultimate closure, rather than utilizing it as daily soil cover during landfill operations as is presently done at most landfill sites.

Although sites in the B.C. interior appear dry (especially during the summer months), spring melt and short term high intensity storm events can cause significant damage if not adequately diverted. Armoured diversion channels with rock berm sedimentation traps are recommended. The size of the channel should be designed with a factor of safety to accommodate peak melts and storm flows from the upstream catchment area.

Diversion ditching to convey clean water run-off from the landfill cover and to intercept up-slope run-on must not only be sized large enough to intercept peak flows, the ditching must be water tight to ensure that most of the water does not leak back into the landfill. It has been our experience at numerous landfills including Hartland, Hope, Knockholt, Premier and others that unlined ditching excavated into soil or rock is not adequate. Diversion ditching must be lined. Design solutions that have been successfully used include PVC lined and rip-rap armoured swales, half round corrugated metal culverts embedded in concrete backfill and fibre-reinforced shot-crete. In each case, typical costs have averaged about $200 per lineal m to construct these systems.