HYDROGEOLOGY OF WASTE ROCK DUMPS

MEND Associate Project PA-1

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EXECUTIVE SUMMARY

Predictions of whether and when a waste rock pile may start to generate acidic water, and how long a pile may release elevated concentrations of metals to the environment, are related on a fundamental level to an understanding of fluid flow within a waste rock pile. Our analysis of the hydrogeological properties of waste rock piles is based on a synthesis of data from four mine sites; Myra Falls, B.C., Island Copper, B.C., Elkview Mine, B.C., and Golden Sunlight Mine, Montana. The emphasis in this study is on pile hydrostratigraphy and the textural properties of the rock mass, spatial and temporal variations in water content within a waste rock pile, temperature profiles within a waste rock pile and their response to the infiltration of water following a rainfall event, and the large-scale hydrogeologic characterization of a waste rock pile inferred from outflow hydrographs recorded in toe drains.

Four hydrostratigraphic models are proposed to characterize waste rock piles; they differ depending upon material types and construction methods. This framework differentiates between porous flow in finer sandy gravel materials and channelized flow in coarser materials. The models are non-segregated coarse-grained rock piles that transmit water rapidly to the base of the pile, non-segregated fine-grained rock piles that are likely to contain a basal saturated zone, segregated rock piles that contain a fine-grained crest zone that may not permit the passage of significant quantities of water; and layered, segregated dumps that contain a finer-grained crest and sandy gravel layers parallel to the face of the rock pile.

Volumetric water content is an important characteristic of the a waste rock pile. It appears to be closely associated with the textural properties of the pile, and it can be used to scan the pile hydrostratigraphy. For a given waste rock pile, at each depth, values of the water content appear fairly stable throughout the year. For the data from Golden Sunlight Mine, attempts to monitor matric potential using heat dissipation sensors, and to correlate changes in matric potential with rainfall events, were generally not successful. Temperature appears to be one of the more reliable parameters to use for tracing the movement of water in those regions of the pile that are reactive and generating heat. The fluctuation of the water table in response to infiltration is affected by the permeability structure of the pile and location within the pile. The permeability structure of the pile is the spatial distribution of permeability values within the different regions of the pile. The data we examine is suggestive of rapid infiltration of water through waste rock piles, although sampling frequencies were not adequate to develop precise estimates of fluid velocities.

A methodology is presented, based on kinematic wave theory, that relates the outflow hydrograph recorded in toe drains to large-scale parameters characterizing the hydraulic conductivity structure of the waste rock pile. The outflow in response to an infiltration event is treated as an integration of the outflows from different channel groups within the pile. Water transfer from the channels to the finer-grained matrix is taken account of in the analysis. Application to the Island Copper data set suggests that the approach holds promise as a means of characterizing large-scale flow processes in a waste rock pile.

Further work is warranted to improve the model in its representation of channelized flow, and to apply the method to rainfall events at a number of different sites to gain insight to the relationship between hydrostratigraphy, and flow responses.

The most significant limitation of the existing database is that no single site provided a complete data record of the important parameters required to characterize the hydrologic behavior of a waste rock pile, and the frequency of sampling was often insufficient for our purposes. In our opinion, to better understand the hydrology of a waste rock pile, the following measurements should be given priority: water content and temperature profiles through the unsaturated zone, water table elevation, volumetric discharge at toe drains, and rainfall and air temperature. Workplans are presented for three types of monitoring studies; a pile assembly study, a pile monitoring study, and a pile disassembly study. It may be advantageous to link these workplans to operations at a low-grade stockpile. It is important to coordinate the suite of measurements made prior to and during the disassembly of a pile.

RÉSUMÉ EXÉCUTIF

Les prédictions concernant la possibilité et le moment où une halde de stériles peut commencer à produire de l'eau acide et le temps qu'elle peut dégager des concentrations élevées de métaux dans l'environnement, sont liées à un niveau fondamental pour comprendre l'écoulement du fluide à l'intérieur d'une halde de stériles. Notre analyse des propriétés hydrogéologiques de ces dernières se base sur une synthèse d'informations obtenues de quatre sites miniers: '*Myra Falls, Island Copper et Elkview Mine*' en Colombie-Britannique et '*Golden Sunlight Mine*' au Montana. Dans cette étude, l'accent porte sur un amas de roches hydrostratigraphique et sur les propriétés de texture de la masse rocheuse, les variations spatiales et temporelles dans la teneur en eau à l'intérieur d'une halde de stériles, les profils thermiques dans cette dernière et leur réaction à l'infiltration de l'eau suite à une chute de pluie, et la caractérisation hydrogéologique à grande échelle d'une halde de stériles qui résulte probablement d'écoulements hydrographiques, enregistrés dans les drains de pied.

Quatre modèles hydrostratigraphiques sont proposés pour établir une distinction des haldes de stériles, ils se différencient selon les types de matériaux et les méthodes de construction. Ce système fait la distinction entre l'écoulement poreux en substances de gravier sablonneux très fin et un écoulement dirigé dans des matières plus rugueuses. Les modèles sont les suivants: des amas de roches à grains grossiers non séparées qui transmettent rapidement l'eau à la base de l'amoncellement, des amas de roches à grains fins non séparées qui contiennent vraisemblablement une zone de base saturée, des amas de roches séparées qui comportent une zone supérieure à grains fins ne permettant peut-être pas le passage de quantités significatives d'eau et des couches de rejets séparés qui renferment des crêtes à grains très fins, et des couches de gravier sablonneux parallèles à la face de l'amoncellement de roches.

La teneur volumétrique en eau s'avère une importante caractéristique de la halde de stériles. Elle semble être directement associée aux propriétés de texture de l'amas de roches et elle peut être utilisée pour examiner l'hydrostratigraphie dans ce dernier. Dans le cas d'une halde de stériles, les mesures de la teneur en eau apparaissent assez stables à chaque profondeur durant toute l'année. En ce qui concerne les données de la '*Golden Sunlight Mine*', des tentatives effectuées pour surveiller un potentiel matriciel qui utilise des détecteurs de dissipation thermique et pour établir une corrélation des changements entre le potentiel matriciel et les chutes de pluie, n'ont pas été fructueuses dans l'ensemble. La température semble être l'un des paramètres le plus fiable pour suivre le mouvement de l'eau dans les régions de l'amas de roches qui réagissent et produisent de la chaleur. Suite à l'infiltration de l'eau, la fluctuation du niveau phréatique est modifiée par la perméabilité de la structure de l'amas de roches et de la location à l'intérieur de ce dernier. La perméabilité de la structure de l'amoncellement comporte la distribution spatiale des mesures de perméabilité dans les différentes régions de l'amas de roches. L'étude des données semble indiquer une infiltration rapide de l'eau à travers la halde de stériles, bien que les fréquences d'échantillonnage n'aient pas été adéquates pour fournir des estimations précises des vélocités de fluide.

Une méthodologie a été présentée: elle se base sur une théorie d'onde cinématique qui signale l'écoulement hydrographique enregistré dans les drains de pied aux paramètres à grande échelle déterminant la structure de conductivité hydraulique de la halde de stériles. Suite à une infiltration d'eau, l'écoulement s'intègre à d'autres écoulements venant de différents groupes de canaux dans l'amas de roches. Le transfert d'eau à partir des canaux jusqu'à la matrice à grains très fins, est noté dans l'analyse. La mise en application selon la série de données de '*Island Copper*' laisse croire que cette approche, considérée comme un moyen pour déterminer les processus d'écoulement à grande échelle dans une halde de stériles, est prometteuse. Un travail plus approfondi est justifié pour améliorer le modèle dans sa représentation d'écoulement canalisé, et pour utiliser la méthode aux chutes de pluie dans certains sites différents, afin de comprendre la relation entre l'hydrostratigraphie et les réactions d'écoulement.

La limite la plus révélatrice de la présente base de données montre qu'aucun site n'a fourni un enregistrement complet des informations des paramètres importants qui sont requis pour déterminer le comportement hydrologique d'une halde de stériles, et la fréquence de l'échantillonnage a souvent été insuffisante pour satisfaire nos objectifs. À nos yeux, la meilleure manière de comprendre l'hydrologie d'une halde de stériles, serait d'accorder une priorité aux mesures qui suivent: par exemple, une teneur en eau et les profils thermiques à travers la zone vadose, une élévation du niveau phréatique, l'écoulement volumétrique aux drains de pied, le régime des pluies et la température atmosphérique. On présente des plans de travail pour les trois catégories d'études mises sous surveillance: entre autres, celles de la construction d'un modèle d'un amoncellement de roches, l'application d'un suivi et le démontage du modèle. Il y aurait peut-être avantage à lier la mise en opération de ces plans de travail à un empilement de minerai à faible teneur. Il importe de coordonner la série de mesures prises avant et pendant le démontage de l'amoncellement de roches.

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CHAPTER 1

INTRODUCTION

At metal mines in British Columbia, hydrogeological processes can play a major role in determining the quality of water draining from a waste rock pile. Better understanding of water flow within and through waste rock piles, including its spatial and temporal variability, is needed to improve our capability to predict the long-term chemical evolution of water draining from waste rock piles. Uncertainty regarding water movement in waste rock piles can be a serious impediment both in predicting the behavior of new waste rock piles, and in decommissioning existing sites.

Recent evidence suggests that the metal concentrations in the water draining from an acid-producing waste rock pile are independent of the volume of water moving through the pile (e.g. Morin et al., 1994). Some success has been reported in predicting concentrations of the dissolved metals such as zinc and copper using equilibrium chemistry models that are tied to the presence of secondary minerals (carbonates, sulfates) that precipitate within the rock pile following oxidation of the primary sulfide and oxide minerals. Thus, it is possible to argue that an improved understanding of fluid flow within a waste rock pile is not essential to the development of predictions of metal concentrations in the water draining from the pile. What is clear, however, is that predictions of when a pile may start to generate acidic water, and how long a pile may release elevated concentrations of metals to the environment, are related on a fundamental level to an understanding of fluid flow within a waste rock pile. While mineralogy and dissolution/neutralization reactions control the chemical characteristics of the water discharging from any particular geochemical zone of a waste rock pile, its hydrogeological properties and connections between different stratigraphic and/or geochemical zones control the changes in water chemistry through time.

Our review of water flow through waste rock piles suggests that the relevant hydrogeological processes are best studied on two scales. One scale focuses on a larger-scale view that attempts to relate water input and drainage from the rock pile to a general characterization of the flow paths within the pile. The second scale takes a smaller-scale view in an attempt to explicitly represent the hydraulic processes internal to the pile. Both approaches are discussed in this report.

The generation of acidic water within a waste rock pile reflects a complex interaction between a number of hydraulic, chemical, and thermal processes. These processes include variably-saturated fluid flow and air circulation in the rock mass above the water table, heat generation and heat transfer in both the aqueous and gaseous phases, oxygen consumption and re-supply, reaction kinetics, and solute transport in the region both above and below the water table. These processes occur in an exceedingly heterogeneous medium containing both a porous matrix and open voids. Following an initial analysis of data from a number of mine sites, we concluded that the following issues or topics were more likely to provide insight to water flow through waste rock dumps:

1. Pile hydrostratigraphy and the textural properties of the waste rock, and how these characteristics influence the hydraulic properties of the waste rock pile, and the patterns of fluid flow,

2. Spatial and temporal variations in water content within a waste rock pile,

3. Temperature profiles within a waste rock pile, and their response to infiltration of water following a rainfall event,

4. The large-scale hydrologic behavior of a waste rock pile inferred from outflow hydrographs.

The reader should note that we do not examine thermal properties of a waste rock pile from the perspective of an ARD prediction, but rather as a tool in understanding water flow through a waste rock pile.

These topics form the main focus of this report. Undoubtedly, other process such as weathering, fines migration and deposition, sealing of channels, settlement of the rock pile, and temporal changes in the spatial distribution of permeable pathways are also important in determining water flow within waste rock piles. These processes will not, however, be addressed in this study because they are both difficult to assess with the available database, and they seem less likely to provide insight to the basic features of water flow through waste rock piles.

We have based our analysis of the hydrogeology of waste rock piles on a detailed examination of data from four mine sites: Myra Falls, B.C.; Island Copper, B.C.; Elkview Mine, B.C.; and Golden Sunlight Mine, Montana. The data were obtained either from the published literature, or in raw form from the mining companies. Except for the Elkview Mine, the waste rock piles at these mine sites contain reactive zones producing ARD. The Elkview Mine, formed from coarse coal refuse, is included in this study because reliable data are available on rainfall rates and water table fluctuations. It does not discharge acidic water. A description of the waste rock piles at each of these mine sites is provided in a subsequent section of this report.

The hydraulic conductivity structure and flow through a waste rock pile is best viewed in the context of a hydrostratigraphic model. The hydrostratigraphic model relates the textural properties of the waste rock, and the spatial distribution of the textural zones within the rock pile, to the expected hydraulic behavior of the rock mass. As discussed in Chapter 2, certain types of coarse rock piles contain open channels embedded within the pile. Throughout this report, we use the term channel to imply a continuous zone of coarse rock with a limited fines content located in the voids between the rock fragments. Flow within these channels can lead to a situation where water penetrates through the rock pile even though moisture contents within the rocks surrounding the channel are lower than that defining the specific retention of the waste rock. This type of behavior is not meaningfully described in terms of a model that represents the entire rock pile as a granular porous medium. We also draw a distinction between these channels, and preferential flow paths that develop within the granular matrix as a consequence of its spatial variability in permeability.

Chapter 2 describes hydrostratigraphic models for waste rock piles, and provides a compilation of the hydraulic properties of waste rock materials. In Chapter 3, we present our evaluation of monitoring data that provides insight to the flow of water interior to a waste rock pile. Chapter 4 describes a promising methodology that relates water input to a waste rock pile to the outflow hydrograph for toe drains, in a way that permits an initial characterization of channels and preferential flow paths within the pile. An assessment of methods for monitoring the hydrogeologic behavior of a rock pile is given in Chapter 5. The report concludes with the presentation of a workplan to address the issues identified as key factors in limiting present capabilities for predicting water flow through waste rock piles.

CHAPTER 5

MONITORING METHODS

While our review of data from four mine sites sheds light on the key hydrologic processes within waste rock piles, it also raises many questions which can only be investigated with additional monitoring and research. In this chapter, we assess monitoring strategies which could provide the data required to better understand the hydrology of waste rock piles. We structure the chapter around the most important hydrogeologic questions to be answered, and suggest monitoring methods to gather the appropriate data.

Before we assess monitoring needs, we note that the most significant limitations of the existing database were that no single site provided a complete and complementary data record of the important parameters required to characterize waste rock hydrology, and that the frequency of sampling was often inadequate for our purposes. For example, water content data was available only for the Golden Sunlight pile, and for that data the temporal sampling frequency is too low to draw inferences about the importance of channel flow on water redistribution. The frequency of rainfall and temperature measurements was too low at Myra Falls to use temperature data to quantify rates of infiltration through the reactive zones of the waste rock pile. To understand the complex interaction between processes, it is essential that both the hydrostratigraphy of the pile be characterized, and a complete set of appropriate measurements be planned.

This call for more complete instrumentation must be balanced by the recognition that characterization of the hydrogeological behavior of a waste rock pile is hampered by the kinds of measurement devices that are available. There is no instrument that can directly identify the geometry of the preferred pathways for the flow through an unsaturated rock pile, nor determine fluid transfer between channels and the porous matrix. We are forced to make inferences on flow behavior from water content measurements, fluid potentials, measurements of parameters such as temperature which may respond to infiltration events, or by using various tracer techniques. These measurements should then be integrated with appropriate models to interpret the significance of the observations. Innovative application of these standard hydrogeological tools and approaches will be necessary to achieve progress in understanding the hydrogeologic properties of waste rock piles.

5.1 Key Questions

Our key questions are given in two lists; one related directly to hydrologic processes, the other related to the link between hydrologic processes and the chemical characteristics of the water migrating through a waste rock pile.

A. Hydrologic processes

1. Where is the flow concentrated within a waste rock pile, and what are the dominant flow mechanisms?

Hydrostratigraphic descriptions of waste rock piles point to the potential for flow in open channels, and through a granular porous matrix. The relative importance of these two regions acting as conduits in the different hydrostratigraphic regions of a pile is not understood, nor do we understand how these mechanisms may vary from pile to pile, nor how they may be influenced by pile construction techniques. The features defining a conduit likely vary in different portions of a rock pile, from pile to pile, and with different moisture regimes (seasonal and geographical differences). In general, at greater depths in the pile, the flow is likely to become more diffuse. Infiltration through waste rock piles can be characterized by monitoring water levels, water contents, and temperatures within the pile. Tracer tests may also indicate the location and rate of the flow through the unsaturated zone.

2. How can we characterize the channels and their role in flow processes?

Channel flow is a fast process compared to matrix flow. In a rock pile composed of coarse rock fragments, with a limited fines content, we expect flow to occur predominantly through partially-saturated channels, for which hydraulic head and water content measurements may not be meaningful. Water may cascade vertically through the unsaturated portion of the pile, perhaps displacing water from intermittent zones of saturation. These saturated zones are likely associated with regions in a pile where finer grain sizes are dominant; such as segregated crest areas, compacted surfaces, and layers of fines parallel to the dump face.

Temperature data, like that collected at Myra Falls Mine, may be suited to characterize channel flow when water infiltrates from hotter to cooler regions in the pile. High frequency sampling, perhaps every 15 minutes, and short distances between measurement points (1 - 2 m) may be required to characterize the movement of individual infiltration events through channels to the water table.

Tracer experiments can also be used to characterize channel flow. A conservative tracer will not be influenced by sources and sinks in the way that temperature can be affected by heat gain from active redox zones and heat loss to the rock mass. The principal limitation of tracer tests is the difficulty obtaining water samples from partially saturated channels.

3. How can we characterize the porous matrix and its role in flow processes?

In finer-grained rock piles, channels may be discontinuous or absent. Infiltrating water moves through a granular matrix due to gravity and capillary forces. In rock piles with open channels, capillary forces will also draw infiltrating water into the porous matrix along the walls of the channel. Between infiltration events, water within the unsaturated zone will be in storage in the finer-grained matrix material. If water contents exceed the retention capacity of the matrix, the water will drain downwards through the matrix toward the water table. For the matrix material, it should be possible to establish lab-based estimates of the relationships between grain size and moisture retention characteristics. Neutron probes can be used to record moisture content with depth. Above the water table, water content measurements can provide information on regions of finer grain sizes (higher water contents) and regions of coarser grains (lower water contents), even if we do not know the grain size distribution within the pile.

Water content will depend not only on grain size, but also on hydrostratigraphic controls on moisture redistribution within the pile. While water content measurements can be used to map water content profiles through a waste rock pile, it will be difficult to draw inferences on flow conditions from these data. If the matrix is partially saturated, matric potential measurements are required to determine the gradient in hydraulic head. Given the difficulty and apparent unreliability of matric potential measurements in reactive zones within rock piles, we do not expect data of sufficient quality to make quantitative inferences on flow rates, flow directions, or for calculations of in situ, unsaturated hydraulic conductivity. Matric potential measurements should be useful in regions of a pile with finer grained matrix, that are non reactive.

The saturated zone at the base of the pile may be the largest reservoir of water in the pile. Water-table elevations can be monitored by piezometers to determine the change in storage in the system and to characterize lateral flow conditions. It will be important to determine the relative contributions of local infiltration through the pile, and that component which may enter the base of the pile from subsurface or surface sources outside the pile. If open channels form a connected network in the saturated zone of the waste rock pile, they may act much like a fracture network, providing the dominant control on fluid flow patterns.

4. What is the relationship between the total discharge from the toe of the pile and the internal flow processes within the pile?

To obtain a water balance for a waste rock dump, it is important to characterize the total infiltration, evaporation and discharge from the pile. The analysis is straight forward if no groundwater enters the pile, and if the discharge is entirely captured at the base of the pile. The discharge can be measured in a toe drain with a calibrated weir. This discharge can be related to infiltrating rainfall, and water movement through the pile. The horizontal gradients measured in the saturated zone, along with total discharge data, can be used to calculate a pile "base-flow" and thus characterize the bulk hydraulic conductivity of the saturated zone. To better understand spatial relationships between metal concentrations monitored in toe drains, and concentrations interior to the pile, water samples should be collected from the boreholes monitoring the water table elevation.

For piles which receive groundwater flow through their sides or base, long-term monitoring of the discharge from the pile should allow one to identify in the hydrograph the regional water flow and the high frequency signals produced by rainfall events (e.g., Island Copper Mine data). The signals produced by the rainfall events can be analyzed with the kinematic wave theory to provide information about the internal hydraulic conductivity structure of the pile.

5. How does hydrostratigraphy change with time as the dump subsides and fines migrate through the pile?

These questions can be addressed by measuring grain size distributions during pile construction, disassembly, or in situ. Longer-term studies of changes in the outflow hydrograph measured in toe drains, interpreted in the context of the kinematic wave model discussed in Chapter 4, may also indicate changes in patterns of flow within a consolidating waste rock pile. Fines migration could be studied with simple column tests similar to tests carried out for graded filter design testing.

B. The link between hydrology and water geochemistry

1. What is the nature of the connection between the dominant flow paths and the other portions of the waste rock pile, especially with reference to those zones which may be geochemically distinct?

This question is central to issues related to the prediction of whether or not a pile may discharge high metal concentrations, and the time scale for metal release. A better understanding of these issues is probably best addressed by hydrostratigraphic and geochemical mapping, carried out in conjunction with pile assembly/monitoring/disassembly studies described in Chapter 6.

5.2 SUMMARY: PARAMETERS TO MONITOR

In light of the questions raised above, and the review of data provided in Chapters 3 and 4, the following parameters should be monitored in an existing pile:

1. Water content

Neutron probes or lysimeters can be used. Neutron probes are likely easier to operate and can be used to generate water content profiles along boreholes (see Golden Sunlight data in Chapter 3). Weekly measurements are recommended in order to track seasonal effects and correlations between grain size and water retention. Calibration of the neutron probe and the possibility of preferential flow along borehole walls are concerns. Installation and monitoring of lysimeters would be difficult and likely requires special designs.

2. Temperature within the pile

At least one thermistor nest, instrumented at regular intervals along the vertical direction, should be installed at the center of the pile. Vertical chains of thermistors should be installed in regions of the pile that are releasing heat due to redox reactions. Temperature can be used as a tracer of water flow near the hot regions of the pile. The need for additional monitoring sites should be evaluated on a case-by-case basis. The temperature of discharge water should also be monitored.

3. Volumetric discharge

Collection drains at the toe of a waste rock pile should be directed over calibrated weirs and the discharges recorded.

4. Water table elevations

At least 3 piezometers should be placed within the pile to characterize flow directions and water stored in the saturated zone below the water table. One piezometer should be placed on the top of the pile and the other two at different levels of the pile slope. The number of piezometers is best tied to individual site conditions. If it is suspected that the pile is gaining or loosing water to the local groundwater system, then additional piezometers should be completed below the base of the pile to allow fluxes to be estimated. If perched water tables are encountered (e.g. Elkview Mine), then piezometers should be completed in both the perched zones and in the main water table below.

5. Meteorological data

Rainfall and temperature data should be recorded to determine the quantity and temperature of water entering the pile. Net infiltration to the pile is likely best characterized by intensive monitoring of changes in water content, or via interception of infiltrating water in lysimeters, at a small number of targeted areas on the surface of the pile.

The monitoring which we describe above should be sufficient to characterize the water flow and hydraulic properties of a pile. However, if the objective is a complete assessment of the acid rock drainage processes, additional parameters should be monitored. Some of these parameters are: water chemistry within the pile and in the total discharge, gas concentrations (O_2 and CO_2), and alteration mineralogy of the pile. In this work, our attention is focused upon water movement within the pile. Monitoring of acid rock drainage parameters not directly related to water movement is discussed by Morin et al., 1991.

5.3 FREQUENCY AND DURATION OF MONITORING

Sampling frequency depends on the time scale of the process that is being tracked within the pile. If the purpose is to track the effect of water infiltrating during a rainfall event on the temperature field and water table fluctuations, the frequency of temperature and the water table elevation measurements should be at least every hour. Our analysis of the four data sets studied in this project indicates that water infiltrating a coarse pile takes only a few hours to travel through the pile.

If the purpose of the measurements is to observe the long term behavior, daily measurements are sufficient. Examples of long term processes include: seasonal effects on temperature and water table elevations, increase of temperature due to the oxidation reactions, and the advance of the thermal front produced by the redox reactions within the pile.

The large scale hydrogeologic behavior of the pile can also be studied on two time scales. On one hand, the characterization of the large scale hydrogeologic behavior of waste rock piles and its relationship to the channelized flow within the pile requires high frequency in the data. Measurements of the outflow of the pile at least every hour are recommended. On the other hand, for the purpose of defining the water budgets and to observe seasonal effects, daily measurements are sufficient.