SURFACE WATER EVAPORATION FROM MINE PITS IN MINNESOTA[1]

John L. Adams, Robert T. Leibfried
Greg J. Spoden, Linda Alderdice[2]

Abstract. Taconite mining on Minnesota's Mesabi Iron Range produces exceptionally large pits, located near major watershed divides. Basic information about how these pits have changed local hydrology is needed for mineland reclamation and impact evaluation of post-mining land-use proposals. Evaporation from mine pits in Minnesota is a major component of a pit's water balance, and is believed to differ from natural lakes because of unique morphology. In a cooperative effort by the U.S. Bureau of Mines and the Minnesota Department of Natural Resources, the evaporation pan coefficient method is being refined for application to mine pits in Minnesota. Two standard Class A evaporation pans were installed, one on land at the study pit, and the other partially immersed in pit water to simulate the pit's energy regime. Pressure transducers and data loggers record average hourly water levels in the pans. Related, on-site meteorological data serves as input for the Modified Penman-Monteith (MPM) method, in an attempt to extrapolate study results to other pits. Limited MPM estimates were consistently lower than in-pit pan measurements. After two open-water seasons, in-pit pan evaporation averages about 600 mm per season, compared to an estimate of 450 mm using published monthly evaporation for lakes and reservoirs in the study area. The average monthly ratio of in-pit to on-land pan evaporation ranges from about 0.6 during May to about 1.7 during October, averaging nearly 1.0 for the season, compared to a published annual coefficient of 0.78 for lakes and reservoirs in the study area. The study will be continued for at least two years.

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[2]John L. Adams is a Mining Hydrologist, Minnesota Department of Natural Resources, Grand Rapids, Minnesota 55744; Robert T. Leibfried is a Hydrologist, Minnesota Department of Natural Resources, Grand Rapids, Minnesota 55744; Greg J. Spoden is Assistant State Climatologist, Minnesota Department of Natural Resources, St. Paul, Minnesota 55108; Linda Alderdice is a Soil Scientist, U.S. Bureau of Mines, Minneapolis, Minnesota 55417.

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INTRODUCTION

The Mesabi Iron Range extends for nearly 90 miles across northeast Minnesota (Figure 1). The Minnesota Mining Directory (Lipp, 1989) lists over 150 exhausted natural ore mines on the Mesabi Range. Some of the natural ore pits have been consumed by taconite mining, resulting in creation of much larger pits, up to several miles long and a mile or more wide. Construction of pits near major watershed divides results in important hydrologic changes.

All Minnesota taconite operations are subject to Mineland Reclamation Rules (Minnesota Rules, Chapter 6130) and Minnesota Statutes (M.S. 103G.297) which direct watershed restoration after mining. One taconite mine in Minnesota ceased operation in 1985, abandoning approximately 1200 acres of pits which are nearly filled with water and are being evaluated for suitability for a variety of post-mining land uses. Other taconite pit complexes will become subject to reclamation regulations and post-mining land use proposals as their ore reserves are exhausted.

Reclamation of mine pits and evaluation of post-mining land-use proposals requires knowledge of pit hydrology in order to answer questions about the rate of filling with water, outlet location and design, and downstream impacts on flooding, drought, aquatic habitat and riparian rights. Traditional water-balance models may be applied to mine pits if the input parameters are reasonably well known. At least three

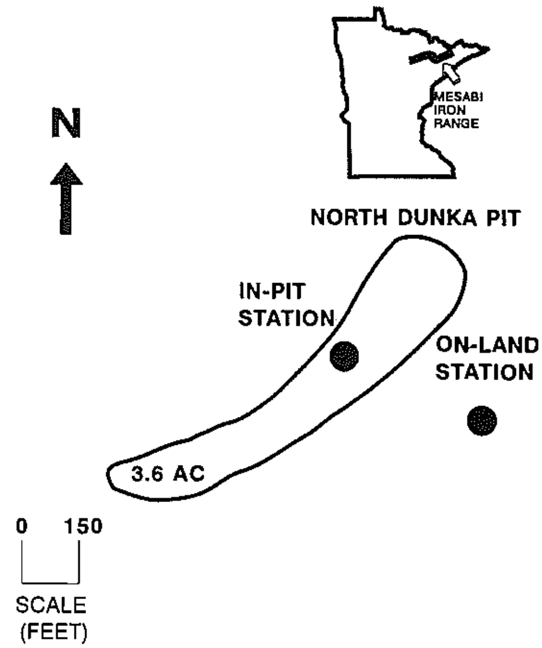

Figure 1. Dunka mine pit evaporation study site.

input parameters, groundwater inflow/outflow, surface water runoff, and evaporation, are poorly defined for mined areas in Minnesota. During the summer of 1989, the Minnesota Department of Natural Resources and the U.S. Bureau of Mines initiated a cooperative agreement designed, in part, to begin quantifying these parameters. Present objectives of the study focus on evaporation losses since evaporation is believed to be a major component of the water balance of water-filled pits. Future studies will focus on other components of mine pit water balance.

The rate and timing of evaporation from mine pits is believed to be different from natural lakes. The morphology of mine pits aids in maximizing heat storage in pit water.

Water depths, sometimes exceeding 100 meters, allow complete thermal stratification. High pit water clarity allows for deep penetration of short wave solar radiation, further increasing total heat storage. In addition, vertical pit walls of exposed rock provide a thermal storage mass not normally found around natural lakes in Minnesota. This rock mass can absorb and radiate heat and may alter the extent and timing of evaporation.

METHODS OF CALCULATING EVAPORATION

There are at least four potential methods of calculating evaporation from a water surface: the energy budget, mass-transfer, water budget, and pan coefficient method. The energy budget method involves measurement or estimation of each component of the energy balance equation. The extent of instrumentation and study time for the energy budget is prohibitive for most impact evaluations by regulatory agencies.

The mass-transfer method has won favor over the more data intensive energy budget method. Lake evaporation by the mass-transfer method is a function of over-water wind speed and vapor pressure difference between the saturated air at the water surface and the air above (Derecki, 1979). Air saturated with water vapor contains only several percent moisture by weight, therefore, differences in upwind and downwind moisture densities are small at best. As a result, sensitive, costly instrumentation is necessary, reducing the practicality of this method for regulatory agency application.

The water budget method works with components of the hydrologic cycle, including 1) precipitation, 2) surface water runoff, 3) groundwater inflow and outflow, and 4) evaporation. Determination of evaporation by the water budget method is generally accomplished by difference and not direct measurement. This means that the other components of the water balance equation must be determined as accurately as possible. In particular, groundwater inflow and outflow, and surface water runoff determinations can cause considerable error in evaporation estimates (Sill et al. 1984). The groundwater and surface water components of mine pit hydrology in Minnesota are poorly defined, at best, making the water budget method impractical at this time.

Simplified versions of mass-transfer or energy budget methods have been developed which utilize available or easily estimated input data. Some of these are presently being used by the Minnesota Department of Natural Resources for impact evaluations concerning lakes and reservoirs, although none have been tested for their application to mine pits. Meteorological data collected at the study site will be used as input for the Modified Penman-Monteith (MPM) method (Rosenberg et al. 1983) for comparison with the in-pit pan evaporation and extrapolation of study results to other pits along the Mesabi Range. The MPM method combines principles of the energy budget and mass-transfer methods to estimate open-water evaporation.

The pan coefficient method involves either estimating or measuring on-land pan evaporation and multiplying it by a pre-determined coefficient to estimate average annual lake evaporation. The coefficient multiplier is necessary since annual, on-land pan evaporation is greater than lake evaporation. Morton (1986), states that although lake evaporation would be equal to evaporation from a pan located in the lake, it would differ significantly from pan evaporation on land. On-land pan evaporation increases more rapidly during the heating phase of the diurnal and annual cycles, and decreases more rapidly during the cooling phase, than corresponding lake evaporation. Consequently, Morton (1979) remarks that seasonal changes in heat storage are not reflected in on-land pan observations, making seasonal estimates of evaporation from deep lakes (e.g., mine pits) impractical using conventional, annual coefficients. However, a pan coefficient of approximately 0.7 is normally used for determination of monthly evaporation for mineland impact evaluations on the Mesabi Range. Seigel et al. (1980), reports that annual coefficients have been incorrectly used for making monthly estimates in many studies.

Application of the 0.7 pan coefficient for monthly or annual mine pit evaporation estimates is subject to criticism because of limited local data, the unique morphology of mine pits, and the inability to develop reasonable monthly estimates. On an annual basis however, on-land pan evaporation can yield a fairly reasonable estimate of open-water evaporation (Derecki, 1979), if the proper coefficient is known. Use of the annual coefficient to make estimates of monthly evaporation can lead to appreciable errors (Morton, 1979).

PAN COEFFICIENT IN MINNESOTA

Pan evaporation data have been published at only three locations in Minnesota: Hoyt Lakes, Lamberton, and Waseca (Figure 2). From this and other limited data, Kohler et al. (1959) developed estimates

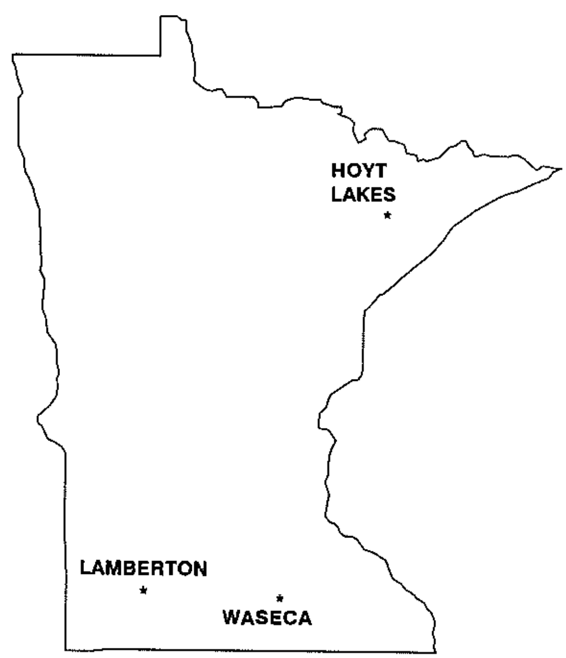

Figure 2. Published pan evaporation sites in Minnesota.

of pan coefficients (Figure 3) and pan evaporation for Minnesota lakes. Baker et al. (1979) developed what appears to be the most detailed estimates of annual pan evaporation for Minnesota (Figure 4). Isolines of mean monthly evaporation have also been estimated for Minnesota by Meyer (1942), and are included in the U.S. Department of Agriculture, Soil Conservation Services's Hydrology Guide for Minnesota (SCS, 1975). Application of these figures is straightforward, however, as noted, they are based on limited data and may not apply to mine pits.

STUDY OBJECTIVE AND DESIGN

The objective of this study is to establish a simple procedure for estimating monthly pit evaporation that is applicable to other mine pits in Minnesota. The study design involves installing two standard evaporation pans, one on-land near the rim of an abandoned pit, and another partially immersed in pit water (Figure 1). By partially immersing a standard evaporation pan in pit water, the energy regime of the pan water closely resembles that of pit water, facilitating reasonably accurate, direct evaporation measurements.

Both the on-land and in-pit sites are equipped with meteorological instruments for data collection to facilitate interpretation of evaporation data, and serve as input for the MPM method. Meteorological data collected at the on-land site includes precipitation, solar radiation, wind direction and speed, relative humidity, air temperature, and pan water temperature.

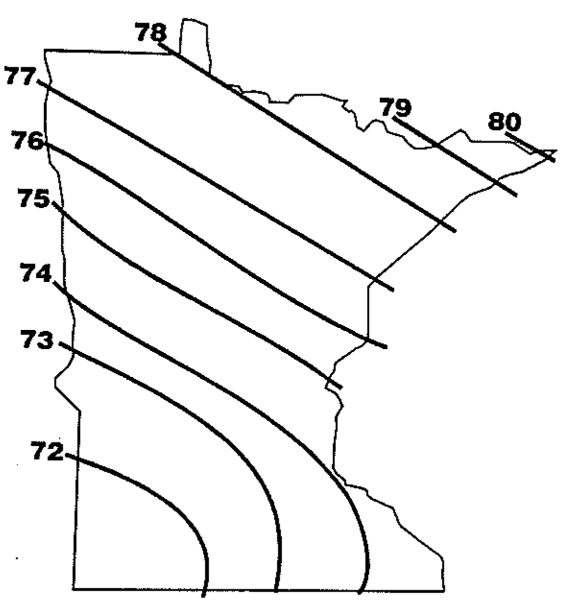

Figure 3. Average annual pan coefficient in percent (Kohler et at., 1959).

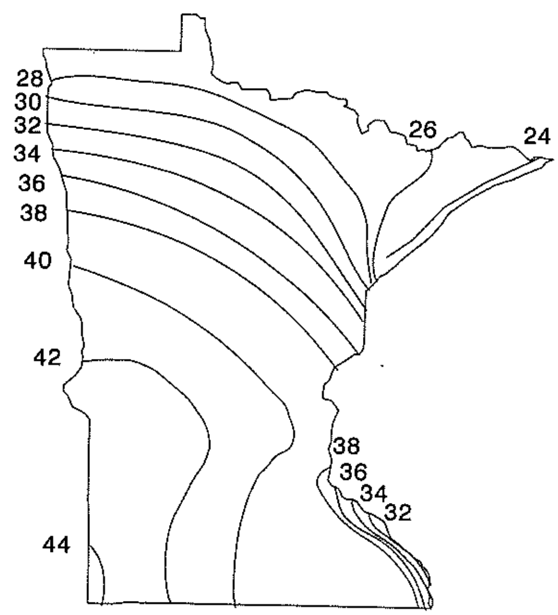

Figure 4. Average annual pan evaporation in inches (Baker et al., 1979).

The study was initiated during the early summer of 1989. Data collected during this first summer were of questionable accuracy due to several design problems, including the lack of wave protection for, and easy access to the in-pit pan. Consequently, data collected during 1989 are not included in this report.

Several design changes during the winter of 1989-1990 resulted in improved data collection during the summer of 1990. All 1990 evaporation data were collected manually using a standard hook gage, with measurements taken three or four times per week. Problems persisted, however, with accurately measuring water depth in the floating pan because of pan movement. In search of a more accurate method of measuring pan water depth, laboratory experiments were run during the winter of 1989-1990 using a low pressure transducer and data logger. These experiments were highly successful, suggesting that transducers could be used to measure hourly pan water depth to within a tenth of a millimeter. Evaporation under simulated rough water conditions was accurately measured by averaging a large number of readings each hour.

However, the accuracy experienced in the laboratory could not be completely duplicated in the field. The transducers were not able to quickly adjust to diurnal pan water temperature changes, giving temporary, erroneous readings. Each morning as pan water temperature rises, the

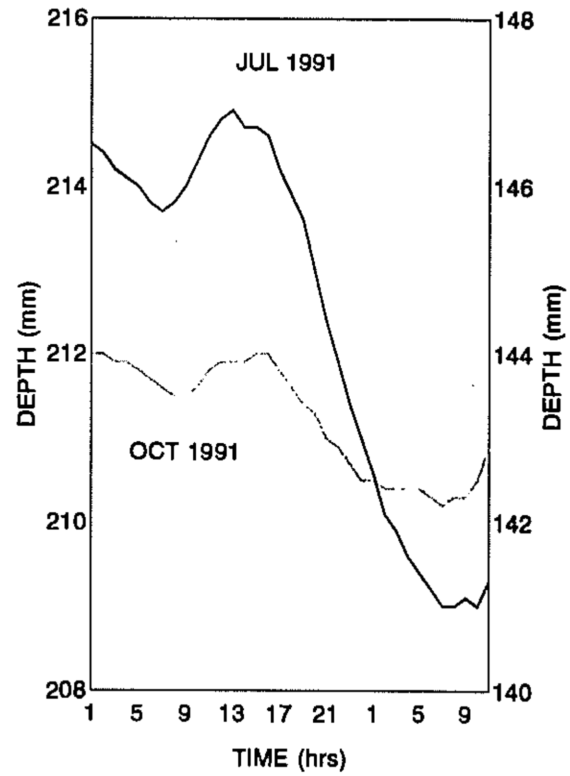

Figure 5. Typical hourly transducer readings for summer and fall.

transducers produce artificially high readings for several hours, simulating the effects of precipitation accumulation. This effect is much reduced or non-existent on cloudy days, but persists on sunny days, even throughout cooler fall weather (Figure 5). The problem was much less evident in the pit pan because of smaller pan water temperature fluctuations due to the moderating effect of the pit water (Figure 6).

The transducer reaction to temperature change eliminates the possibility of acquiring hourly evaporation, but does not eliminate the capability of acquiring accurate daily evaporation readings. Typical

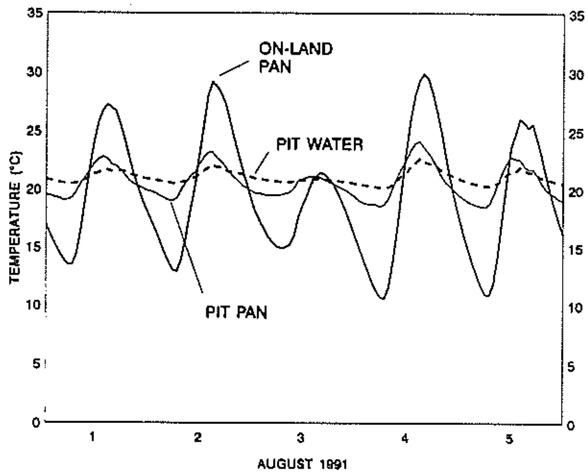

Figure 6. Comparison of pit water temperature with pan water temperature.

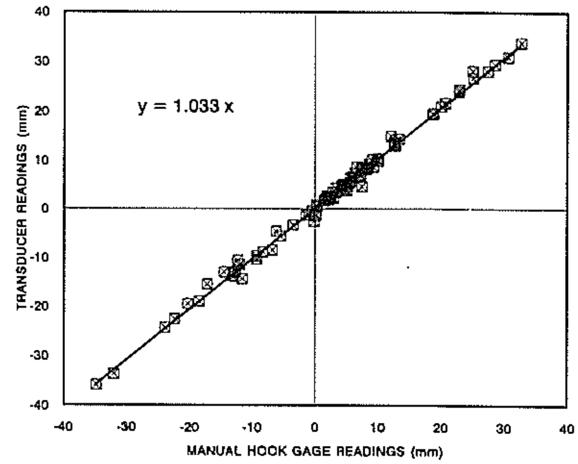

Figure 7. Plot of 84 daily transducer readings vs. hook gage readings.

hourly readings shown in Figure 5 reach a low point at approximately 6 a.m. CST each day. Twenty-four readings taken at 6 a.m. CST each day are essentially identical to hook gage readings taken at approximately the same time each day (Figure 7).

STUDY RESULTS

Results contained in this report are based on only two seasons of data collection, one lacking early spring readings. None-the-less, several tentative conclusions can be drawn.

Pan Water Temperature

Partially immersing a standard evaporation pan in pit water results in daily maximum and minimum pan water temperatures consistently within 1 or 2 degrees celsius of actual pit water temperature, compared to 5 to 10 degrees deviation for an on-land pan (Figure 6). Richter (1966) found that a partially immersed pan, 62 cm in diameter and 60 cm deep closely followed the heat budget of the surrounding water. The standard evaporation pan used for this study, 120 cm diameter by 25 cm deep, prevented mixing with deeper water, thereby allowing some temperature exaggeration of pan water. This effect may have slightly increased evaporation from the pit pan, particularly during hot days. Examination of spring and fall data, in comparison with MPM method estimates, will guide future conclusions about the significance of slight temperature deviation.

Wind

A major environmental factor affecting evaporation, wind is much reduced at the pit water surface compared to the on-land site (Figure 8). The reduction in wind is expected at the study site because of the small size of the pit. Larger pits should not exhibit this effect, depending on their

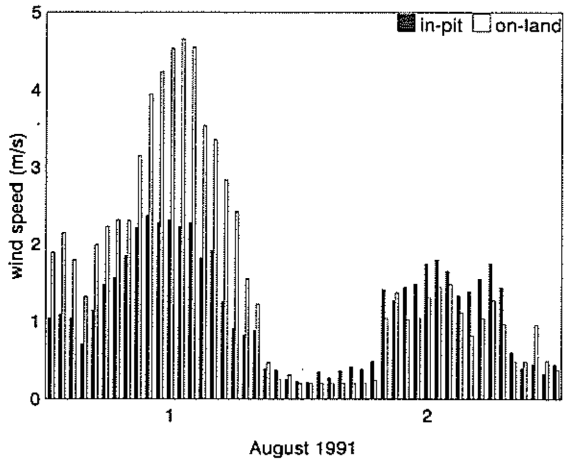

Figure 8. Comparison of in-pit wind with on-land wind for a selected time in August 1991.

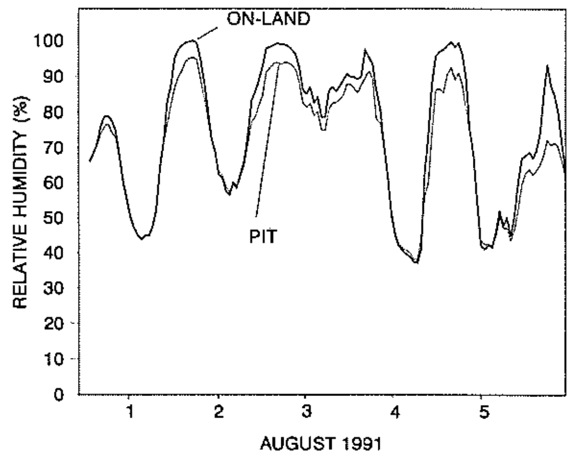

Figure 9. Comparison of in-pit with on-land relative humidity for a selected time in August 1991.

orientation. The effect of wind on evaporation will be evaluated through a sensitivity analysis with the MPM method. It is expected however, that increased wind on larger pits will result in evaporation estimates greater than those measured at the study site.

Relative Humidity

Relative humidity (RH) is another environmental factor which greatly affects evaporation. A comparison of RH at the two sites (Figure 9) shows surprisingly little difference. This may be attributed to the small size of the study pit, or perhaps the location of the evaporation pans in relation to prevailing westerly winds. It is possible that air columns moving over the pit do not have enough time to pick up measurable amounts of moisture before reaching the in-pit RH sensing unit. It is also possible that the on-land RH sensing unit, located generally downwind of the pit, is affected by humidity from the pit water. As with wind, the effects of RH on evaporation will be evaluated through a sensitivity analysis with the MPM method.

Open-Water Season Evaporation

Manual data collection during the 1990 open-water season allowed calculation of monthly evaporation for each site. During the 1991 open-water season, transducer readings allowed calculation of daily and monthly evaporation readings. Monthly evaporation for the two seasons are summarized in Table 1, along with estimated average monthly lake evaporation for the study location using graphs from the Hydrology Guide for Minnesota (SCS, 1975). Total May through October evaporation from the in-pit site for the two seasons of data is greater than expected, averaging about 600 mm compared to an estimated 450 mm for lakes and reservoirs using the graphs.

Pan Coefficients

Average monthly and seasonal (May-Oct.) pan coefficients for the study site (Table 2) were calculated using measured in-

Table 1. Monthly Evaporation for 1990-1991 Open-Water Season.

	In-Pit Pan Evap. (mm)			On-Land Pan Evap. (mm)			
Month	1990	1991	Ave.	1990	1991	Ave.	Lakes[1]
May	67	49[2]	58[2]	118	71	95	48
June	79	153	116	137	157	147	61
July	120	137	129	154	127	141	91
August	125	142	134	148	132	140	104
Sept.	93	109	101	83	65	74	89
October	70	64	67	42	36	39	56
Season	554	654[2]	604[2]	682	588	635	449

[1]From Figures 8-8 through 8-13 of the Hydrology Guide for Minnesota (SCS, 1975).
[2]Includes only May 17-31 for the 1991 Season.

Table 2. Average Monthly and Seasonal Pan Coefficients.

Month	1990	1991	Average
May	.57	.69	.6[1]
June	.58	.97	.8
July	.78	1.08	.9
August	.84	1.08	1.0
September	1.12	1.68	1.4
October	1.67	1.78	1.7
Seasonal	0.81	1.11	1.0[1]

[1]Includes only May 17-31 for 1991 data.

pit and on-land pan evaporation data from Table 1. The average seasonal coefficient, based on two seasons of data, is nearly 1.0, implying that seasonal evaporation from the study pit approximates on-land pan evaporation. The seasonal coefficients are notably higher than the recommended 0.78 average annual coefficient for lakes and reservoirs in the study area (Figure 3). More importantly, average monthly coefficients range from a spring low of about 0.6 to a fall high of about 1.7. The coefficients for most months vary greatly from the recommended annual coefficient (0.78), which has been used to predict both annual and monthly evaporation.

There are several possible explanations for these differences, although most noteworthy is the difference in energy budget between mine pits and lakes. Energy budget differences are reflected in increasingly larger monthly coefficients from spring to fall. Most natural lakes, with shallower water, would probably have higher spring coefficients, lower fall coefficients, and lower average coefficients for the open-water season.

The Modified Penman-Monteith (MPM) Method

Figure 10 shows a comparison of daily in-pit evaporation measurements with estimates using the MPM method for the month of August, 1991. August was randomly selected for an initial comparison. Input data for the MPM method were collected at the in-pit site, except for solar radiation from the on-land site. August daily evaporation estimates made with the MPM method are consistently lower than in-pit pan measurements, averaging 3.4 mm and 4.6 mm per day, respectively. Possible reasons for this difference include the slight temperature exaggeration of in-pit pan water, location of the pan in the pit, or perhaps the nature of the MPM method input data. For example, average daily wind speed and average daily vapor pressure serve as inputs. It may be that use of average daily input values results in under-estimation of actual evaporation since most evaporation occurs during windy, low-humidity, daylight hours. The summation of two 12-hour MPM method estimates per day may result in better correlation.

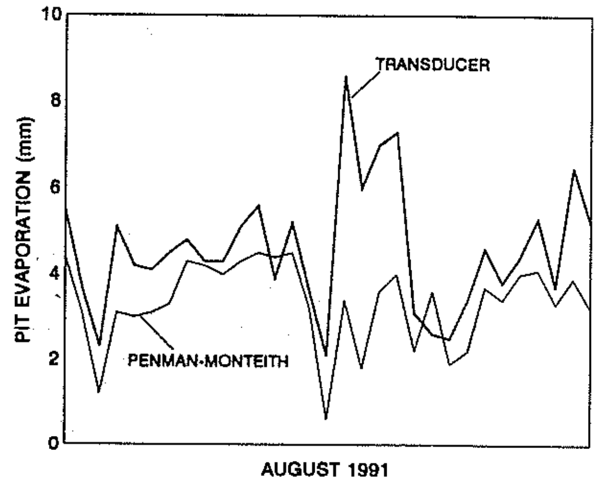

Figure 10. Comparison of estimated daily evaporation using the Modified Penman-Monteith Method vs. in-pit pan evaporation, for August 1991.

CONCLUSIONS

Pressure transducers successfully measure 24-hour water level changes in evaporation pans, but are not successful at measuring hourly water levels due to their inability to rapidly adjust to water temperature changes. Twenty-four hour readings, taken immediately before the start of each day's temperature rise, are comparable to manual hook gage readings. The transducers also have the advantage of providing complete seasonal, 24-hour readings, with no breaks in data.

Based on two years of open-water season data, seasonal evaporation from the in-pit pan is averaging about 33% higher than would be expected from natural lakes or reservoirs in the area. This does not include an adjustment for possible effects of slight temperature exaggeration of water in the in-pit pan, or pan location in the pit. The average open-water season pan coefficient is calculated at 0.95, suggesting that seasonal pit evaporation approximates on-land pan evaporation. Average monthly pan coefficients range from about 0.6 during spring to about 1.7 during fall, allowing calculation of monthly water balances where monthly pan evaporation is known or measured.

Estimates of daily evaporation for August 1991 made with the Modified Penman-Monteith (MPM) method average 27% lower than the in-pit pan measurements. It is intended that the MPM method be used to extrapolate the results of this study to other pits across the Mesabi Range, although some adjustment of the input data, such as separating day and night segments, may be necessary. Comparison of estimates for other months, particularly spring and fall when water temperature exaggeration in the in-pit pan is reduced or absent, will facilitate a better understanding of the cause of the difference.

Results of this study, particularly definition of monthly pan coefficients, will better define the evaporation component of the hydrologic cycle of mine pits, and will help focus future water balance studies.

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