APPENDIX A

HYDROLOGY

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1.0 GOALS AND PURPOSE OF THE APPENDIX

Developing a mine plan of operations, designing operational procedures, and designing hydrological control structures and other best management practices (BMPs) to prevent environmental impacts all require accurate knowledge of the variables associated with hydrological conditions at a mine. Of particular importance is proper characterization of baseline hydrological and hydrogeological conditions so that the extent of impacts to hydrologic and other related resources can be minimized or avoided. Mining operations must accurately consider two main hydrologic components when planning operations: (1) process system waters, often referred to as the process circuit, and (2) natural system waters or the natural circuit. The primary goal of this appendix is to outline the methods and analytical procedures commonly used to characterize the natural system waters at a mine site. Included are descriptions of the rationale and methods for characterizing surface water hydrology, ground water hydrogeology, and surface water-ground water interactions. The characterization, handling, and treatment of process system waters are discussed in Appendix E, *Wastewater Management*.

Natural system waters are those associated with the natural hydrological cycle, such as ground water and meteoric water from precipitation, snowmelt, evaporation, and runoff. For mining operations, important data for establishing baseline hydrological conditions include the measurement of precipitation, runoff, and losses or abstractions from precipitation (Barfield et al., 1981). Impact evaluations and the proper design of detention structures, diversions, culverts, pregnant ponds and barren ponds, tailings dams, and other facilities depend on accurate characterization of hydrological parameters.

2.0 HYDROLOGICAL CYCLE

The term “hydrological cycle” generally is used to describe the continual circulation and distribution of water through all elements of the environment. The hydrological cycle is a convenient means for describing the interrelation between six fundamental processes: condensation, precipitation, evapotranspiration, infiltration, surface runoff, and ground water flow.

The hydrological cycle can be viewed as beginning with the evaporation of water from the ocean. Evaporated moisture then collects in the air, and under proper conditions, condenses to form clouds. Ultimately, the clouds may release this water as precipitation which subsequently collects on land and is dispersed in one of three ways. The largest part is temporarily retained in the soil near where it falls. This portion is returned to the atmosphere by evaporation and transpiration by plants (Linsley et al., 1975). Another portion of this water infiltrates through the soil and recharges ground water reservoirs. The final portion of the precipitation runs off the surface and collects in stream channels and lakes. Under the influence of gravity, the ocean receives portions of both the stream flow and ground water flow and the cycle begins again.

Obtaining adequate data for predicting and determining hydrological processes at proposed mining operations presents significant challenges. These processes are very complex and have high variability, making measurement and characterization for predictive purposes difficult. Understanding the hazards and benefits of the hydrological cycle will assist in proper mine operations and contribute to environmental protection. In addition, hydrologic processes are related to other important resources such as water quality, aquatic life, vegetation, wetlands, and terrestrial wildlife.

3.0 HYDROLOGICAL IMPACTS

Characterizing hydrology at a mine site is necessary to identify the area(s) that would be affected by mining activities; determine impacts to the related physical, chemical, and biological resources; and develop appropriate monitoring programs and mitigation measures. Background hydrological conditions should be characterized in order to provide a baseline from which changes can be measured or predicted and to identify environmental conditions that could be potentially impacted by mining activities. The intent of the characterization is to determine the nature and extent of ecological impacts from mining-related changes in the hydrological system. If past or present mining activities have been underway, then the hydrological effects from these sources should be examined. It is important that the scope of evaluating hydrological baseline conditions and hydrological effects of a mine extend beyond actual mine site boundaries in order to place the project in the context of its watershed.

Hydrological studies can be used to predict future impacts from proposed mining activities. Potential mining-related impacts to hydrology can be separated into surface and subsurface systems. Surface and subsurface hydrological systems are likely to interact with one another and they can impact other related resources.

3.1 Surface Impacts

Many surface water hydrological impacts are related to mine construction and the location of facilities. Road construction, logging, and clearing of areas for buildings, mills, and process facilities can reduce infiltration and increase the amount of surface runoff to streams and other surface water bodies. This can increase the peak flow and the total stream discharge associated with a given storm event. Unusually high peak flows can erode stream banks, widen primary flow channels, erode bed materials, deepen and straighten stream channels, and alter channel grade (slope). In turn, these changes in stream morphology can degrade aquatic habitats. Channelization (i.e. straightening) can increase flow velocities in a stream reach, potentially affecting fish passage to upstream reaches during moderate to high stream flows. Increased erosion upstream and the resulting sedimentation downstream can impact spawning gravels, egg survival and emergence of fry, as well as degrade benthic food sources. A detailed discussion of erosion and sedimentation as related to mining is provided in Appendix H, *Erosion and Sedimentation*.

The location of mining facilities frequently requires the construction of stream diversions and/or storm water ditches that control and divert runoff from upland watersheds. Typically, these structures are used to prevent unpolluted water from contacting potentially degrading materials, such as waste rock, or flooding over disturbed areas and degrading water quality. Drainage control structures also are used to prevent operational difficulties which could occur at the site. Although these structures may mitigate and control potential impacts from flooding or erosion from disturbed areas, they often alter or change natural drainage patterns in a watershed, which, in turn, can impact vegetation resources, wetlands, and wildlife habitat.

The discharge of process waters potentially can affect water quality and lead to impacts to resources such as aquatic life. Parameters associated with wastewater treatment and discharge are discussed in Appendix E, *Wastewater Management;* those associated with the management of solid wastes, such as waste rock and tailings, are discussed in Appendix F, *Solid Waste Management.*

Stream flow effects caused by mining operations relate directly to potential impacts in water quality. It is common for many water quality constituents to correlate inversely with stream flow (i.e., chemical concentration increases with decreasing stream flow). This is usually true for the concentrations of total and dissolved metals and most chemical constituents that occur in higher concentrations in subsurface formations than in surface soils. Some chemical constituents, however, correlate positively with stream flow during the beginning stages or “first flush” of a runoff event (i.e., increasing concentrations with increasing stream flow). This condition is sometimes observed with constituents that are associated with surface soils, such as acid salts, or land applied pollutants such as pesticides, herbicides, and nitrates, and constituents that are transported as suspended particles. After this initial increase which is sometimes observed, constituent concentrations generally decrease with the increasing volume of runoff. As described in Appendix B, *Receiving Waters,* water quality data must be collected with consideration given to the varying effects of stream flow at a site.

Withdrawals from streams also can impact aquatic life, particularly fish. Reduced stream flow can potentially affect critical habitat requirements. Fish have different flow requirements at different times of the year and these requirements vary for different species. Specific flows are required for spawning, maintenance of fish redds, fry emergence, juvenile rearing habitat, and adult passage. For these reasons, water withdrawals are often mitigated by establishing instream (minimum) flow requirements at critical times of the year. This requires adequate baseline characterization of hydrologic flow conditions throughout the year and characterization of the available habitat(s) associated with the fishery. Withdrawals of surface water can also reduce naturally occurring high flows that occur during high runoff periods. High flow events are often periodically required within a stream to entrain and transport sediments that were deposited during low flow periods when low peak velocities caused sediment deposition. These are known as channel maintenance flows. Channel maintenance flows are periodically required for a channel to maintain sediment transport capacity without aggrading, filling pools, and changing channel morphology, all of which can also affect aquatic habitat. These impacts are discussed in more detail in Appendix H, *Erosion and Sedimentation*.

3.2 Subsurface Impacts

Potential impacts to ground water flow regimes primarily occur from mine dewatering activities and/or pumping water supply wells (Figure A-1). Dewatering (i.e., pumping ground water from) mine workings, adits, or open pits is required when the mine elevation extends below the potentiometric surface in confined aquifers or below the water table in an unconfined aquifer. Pumping ground water lowers the water table in the immediate area of a well, creating a "cone of depression" which extends radially outward from the well. The radius of drawdown depends on the level that the water table is lowered by the well, the pumping rate, the hydraulic conductivity of the aquifer, and the homogeneity of the aquifer. Water supply wells located close to one another may have cones of depression that overlap, creating a cumulative effect on the drawdown of the water table. When this occurs, the drawdown at a given point becomes the sum of the drawdowns caused by all of the wells (Linsley et al., 1975). A dewatered mine acts as a large diameter well; consequently the water table in an aquifer can be drawn down for a relatively large radial distance. Drawdown can affect the direction of ground water flow by shifting gradients and lines of flow toward the mine or well field.

Drawdown of an aquifer potentially can lead to reduced spring and seep flows and reduced surface water flows in streams that are gaining with respect to ground water (Figure A-1). These effects can impact wetlands associated with springs and riparian zones associated with streams. A reduction in stream flows can also affect aquatic habitats and fish populations. A regional lowering of the water table can impact neighboring water supply and irrigation wells. Water yields from local wells can be reduced or wells may need to be drilled deeper to account for the decreased elevation of the water table or potentiometric surface. Adequate characterization of ground water and hydrogeology is often difficult, especially for fracture-flow conditions. However, sufficient characterization of hydrogeology is required to predict impacts that could occur on local and regional scales.

In areas where ground and surface waters interact due to varying influent and effluent conditions, mining impacts to ground water quality can result in impacts to surface water quality. The factors associated with interacting ground and surface water and resulting impacts to water quality are discussed in Appendix B, *Receiving Waters.*

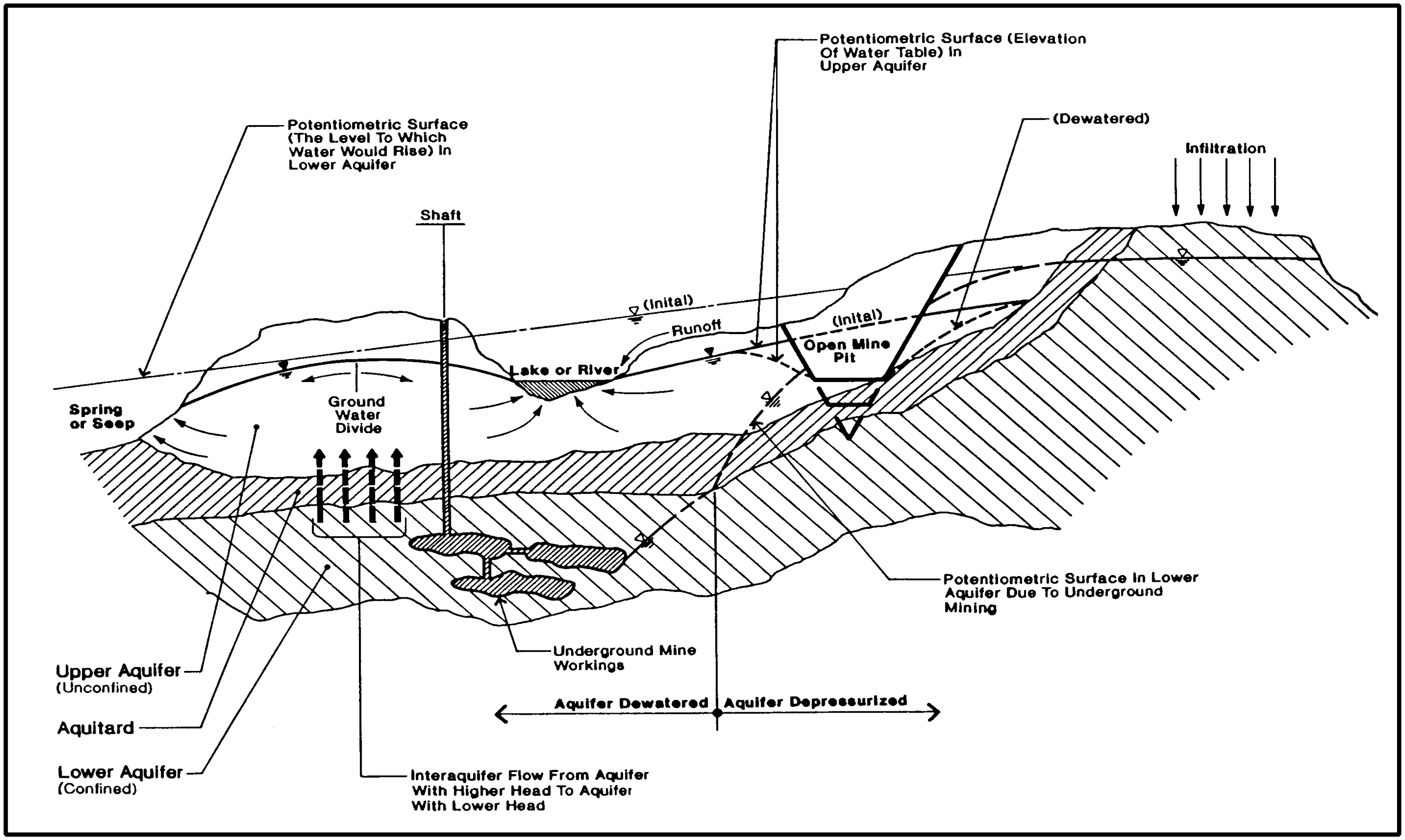


Figure A-1. Ground water flow systems affected by mining (Siegel, 1997).

4.0 METHODS TO MEASURE AND PREDICT HYDROLOGICAL PROCESSES

The design of water collection, storage and treatment facilities at mine sites depends on adequately characterizing the hydrologic system in the vicinity of the site. Precipitation, losses from precipitation (i.e., interception, infiltration, and evapotranspiration) runoff, and stream flow are perhaps the most important parameters to measure during baseline studies. Estimates of the hydrological inputs to a mine and the design of detention structures, retention ponds, culverts, pregnant and barren solution storage ponds, and diversion channels depend on probabilistic determinations of rainfall and runoff events that are developed from historical data. Van Zyl et al. (1988) indicate that short-duration, high-intensity events, large snow-melt events, or extended wet periods are the most important rainfall-runoff events to consider during heap-leach facility design. Unfortunately, rainfall-runoff parameters and probabilistic determinations of future rainfall-runoff events are among the most difficult to accurately determine.

Mines often are located in remote areas or in watersheds lacking historical precipitation and runoff data sufficient to accurately develop return-period and flood-frequency relationships. For this reason, it is important for the hydrologist to incorporate the most rigorous estimates possible given the cost, scope, and data available. Methods for measuring precipitation and runoff and developing probabilistic distribution functions for these data are briefly outlined and compared below. For more detailed information, the reader is referred to Barfield et al. (1981), who provide an excellent compendium of hydrological methods and analyses for mining operations.

4.1 Precipitation

Precipitation depth-duration-frequency information for the United States is available for numerous, widespread climatological stations managed by the U.S. Weather Service and published in atlases by the National Oceanographic and Atmospheric Administration (NOAA). These historical data also are available electronically on magnetic tape and compact disk. Often, these are the only data initially available to mining operations and they serve as the basis for developing probabilistic relationships to use in designing hydrological structures and evaluating inputs for water balance determinations. Actual measurements of precipitation and runoff within the specific watershed of a mine are preferred and should be used whenever possible to develop probabilistic storm frequency relationships and design hydrological structures. Since remote mine areas usually lack the long-term historical data necessary to develop accurate probabilistic relationships, most mine projects need to establish a network of climatological stations and stream-flow monitoring stations to collect records for their watershed(s).

Mean areal precipitation within a watershed or in sub-basins often is used to develop rainfall-runoff probability relationships and for input to other hydrological analyses. The accuracy of these values, or of the historical relationships developed from them, depends on the density of precipitation gages throughout a basin. Studies conducted to analyze precipitation gage density and the errors associated with using these data for estimating runoff and stream flow conclude that a higher density of gages is required where topography is more complex and where convective thunderstorms can be expected to provide significant hydrological input to the system (Eagleson, 1967; Johanson, 1971; Bastin et al., 1984). Linsley et al. (1975) provided the following general guidelines for precipitation station density based on climatic conditions and topography:

- One station per 600 to 900 km^2 (230 to 350 mi^2) in flat regions of temperate, Mediterranean, and tropical zones with relatively high rainfall;

- One station per 100 to 250 km^2 (40 to 100 mi^2) for mountainous regions of temperate, Mediterranean, and tropical zones; and

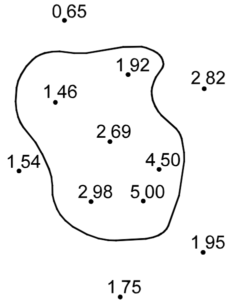
- One station per 25 km^2 (10 mi^2) for small intricate mountainous regions with irregular precipitation.

It is important to note that the accuracy of developed probabilistic distribution functions for rainfall-runoff events for a specific basin will greatly increase over time as the density of gages increases. This is particularly true in basins where brief high-intensity rainfall events can occur in localized areas yet provide significant flow and inputs to a mine operation located lower in the watershed. Three common methods are used to obtain mean areal precipitation from a network of precipitation gages: (1) the arithmetic mean, (2) the Thiessen polygon method, and (3) the isohyetal method. Figure A-2 depicts examples using these methods. The arithmetic mean is a simple average of the stations and is considered the easiest to apply but the least accurate. The other methods apply weighting criteria based on the distances between rain gages (Barfield et al., 1981). The Thiessen method determines weighted areas for each gage based on polygons drawn by perpendicular bisectors between gages. The weighting factor for the isohyetal method is determined by the area of the watershed enclosed between adjacent isohyetes or lines of constant rainfall. The isohyetal method is considered the most accurate of the three methods; however, the Thiessen method has an advantage in that weighting factors for precipitation gages remain historically constant as long as the measurement network has not changed. A detailed discussion of the application of these methodologies is presented by Linsley et al. (1975) and Barfield et al. (1981).

Mean areal precipitation can be evaluated using kriging techniques. Kriging is actually a collection of methods with which to analyze spatial data. It was originally derived for geostatistical analyses and prediction. In general, kriging uses linear regression techniques to minimize the error associated with the estimate of a new point. The estimate is made from a prior covariance model developed from the entire network of data points. In effect, kriging statistically evaluates data from an entire set of spatial data, such as a network of precipitation gages, to make estimates of interspatial data. The output can then be used to develop an isohyetal map similar to that described above. The difference between the two techniques is that the standard isohyetal method uses linear interpolation between two precipitation gages to estimate values between two points. Kriging uses statistical methods to estimate values between two points, taking into account data from other nearby gages. Karnieli and Gurion (1990) described the use of kriging to map areal precipitation and applied it to historical precipitation data for the State of Arizona. Kriging is the most intensive technique to evaluate areal precipitation and specific software is required. For most mining scenarios, however, it would provide better estimates of precipitation inputs, especially in areas with complex topography and in areas where precipitation is spatially more variable. Use of this technique would help to minimize errors associated with rainfall-runoff measurements and to develop more accurate probabilistic relationships over time.

As previously indicated, historical rainfall data are used to develop probabilistic relationships for rainfall and/or runoff events. These relationships describe the frequency or probability of occurrence (i.e., return periods) of rainfall or runoff events. Some common methods for developing these relationships are the Log-Pearson Type III distribution, the Extreme Value Type I Distribution, and the Gumbel Distribution. The methods for developing these relationships are described in various hydrologic manuals and will not be described here (see U.S. Bureau of Reclamation, 1977; Linsley et al., 1975; Barfield et al., 1981). The hydrologist should consider the ultimate use of the data when choosing the methods to determine mean areal precipitation. The specific method used is not as critical to simply characterize the average conditions of a site, such as for a NEPA analysis, as when being applied to hydrologic design, such as for sizing a storage pond or runoff control structure.

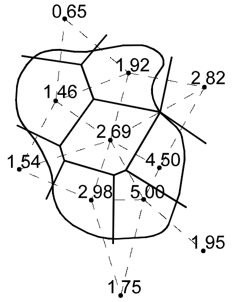
Van Zyl et al. (1988) described an application of the Weibull (1939) formula that utilizes available historical snow pack data to develop probabilistic relationships for snow melt. They indicated that local snow data often are not available for a particular basin of interest and that historical snow course data obtained by the Natural Resource Conservation Service (formerly, the Soil Conservation Service [SCS]) must be used. Figure A-3 shows an example of a probability/return period relationship developed for a snow pack. These types of relationships are similar to those developed for precipitation and runoff events. Linsley et al. (1975) indicated that the best methods to estimate runoff from snow pack are based on simple air temperature, rather than more complicated analytical models that incorporate wind speed, relative humidity, solar radiant flux, and other variables. They suggested methods using a degree-day or degree-hour factor and the average probability of occurrence with elevation. These data typically are available for specific regions of interest. McManamon et al. (1993) described a GIS method for combining snow-water equivalent measurements with other watershed physical parameters to provide better estimates of runoff from snow pack. The design engineer should note, however, that the prediction of runoff from snow-pack analyses is complicated by other hydrological factors such as ground water storage, antecedent soil-moisture deficiency, and the amount of precipitation that occurs during runoff periods (Linsley et al., 1975).



Arithmetic mean:

$$\frac{1.46 + 1.92 + 2.69 + 4.50 + 2.98 + 500}{6} = 3.09 \text{ in.}$$

(a)



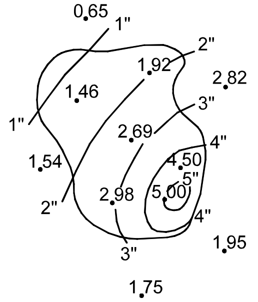
Thiessen method:

Observed precip. (in.)	Area* (sq. mi.)	Percent total area	Weighted precipitation (in.) (col.1 x col.3)
0.65	7	1	0.01
1.46	120	19	0.28
1.92	109	18	0.35
2.69	120	19	0.51
1.54	20	3	0.05
2.98	92	15	0.45
5.00	82	13	0.65
4.50	76	12	0.54
	626	100	2.84

Average = 2.84 in.

* Area of corresponding polygon within basin boundary

(b)



Isohyetal method:

Isohyet (in.)	Area* enclosed (sq. mi.)	Net area (sq. mi.)	Avg. precip. (in.)	Precipitation volume (col.3 x col.4)
5	13	13	5.3	69
4	90	77	4.6	354
3	206	116	3.5	406
2	402	196	2.5	490
1	595	193	1.5	290
<1	626	31	0.8	25
				1634

Average = 1634 ÷ 626 = 2.61

* Within basin boundary

(c)

Figure A-2. Areal averaging of precipitation by (a) Arithmetic Mean, (b) Thiessen Method, and (c) Isohyetal Method (Linsley et al., 1975).

Probabilistic relationships, such as those of Figure A-3 or those published by NOAA, provide maximum precipitation depths or intensities for certain durations and frequencies of occurrence. These data can provide peak-flow or runoff estimates for use in designing hydrologic facilities and structures. In addition to peak flow data, modern design criteria often requires more detailed information regarding the runoff hydrograph. Developing runoff hydrographs typically requires temporal information for storm events (i.e., time versus precipitation intensity relationships) (Barfield et al., 1981).

A plot of the distribution of rainfall intensity versus time is called an hyetograph. Methods to develop design hyetographs (also termed design storms) use theoretical or average time distributions that are based on actual storm events (see summaries in Chow et al., 1988 and Koutsoyiannis, 1994). The time distribution of rainfall intensity associated with a storm greatly affects the quantity and time distribution of runoff. Design storms are created to study or predict theoretical storm runoff for the design of structures, drainage, or containment ponds. The methods commonly used to create design hyetographs can be divided into three categories as described below (Chow et al., 1988; Koutsoyiannis, 1994).

The first category uses pre-selected time distributions such as triangle, bimodal, or uniform distributions. The most commonly used of these methods is that outlined by the Natural Resource Conservation Service (NRCS [formerly SCS]) and is described by SCS (1972). This method uses two theoretical time distributions known as Type I, and Type II distributions. The Type I distribution is recommended for use by NRCS for general application in Alaska and Hawaii; however, an additional distribution has been added by the NRCS known as the Type I-A. The Type I-A distribution produces less severe peak runoff rates than the Type I distribution and is more suited to simulate storm patterns associated with the coastal regions in the northwest United States. For this reason, the Type I-A distribution is recommended for use in Washington and Oregon and should also be considered for use in southeast Alaska. The climate of southeast Alaska differs substantially from that of inland Alaska and is more closely related to that of British Columbia, Washington, and Oregon. The Type II distribution is applicable to the remainder of the United States. A major problem with using these methods is that two or three average distributions are not adequate for all types of storms or for all areas where they are recommended for use. Another major problem is that the runoff hydrographs produced from these methods do not have any real measure of the probability or frequency of occurrence. Thirdly, these distributions base all design events on a 24-hour distribution. Despite these problems, average time distributions, particularly the NRCS distributions, are commonly used for design studies because of their simplicity.

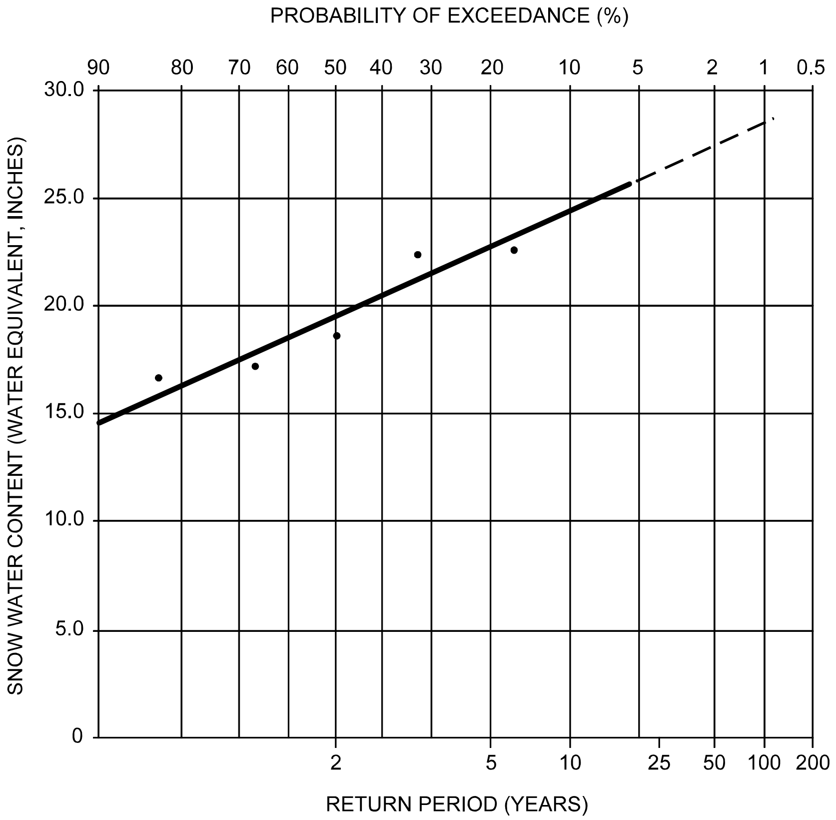


Figure A-3. Typical snowpack frequency curve (Barfield et al., 1981).

The second category of methods is based on regionalized average distributions and the probabilistic occurrence for that time-intensity distribution. An example of this type of distribution is described by Huff (1967). These methods are based on better probabilistic/statistical approaches than those described above. However, Koutsoyiannis (1994) indicated that the exact determination of the probability of the resulting runoff hydrograph is still ambiguous for use in design.

The third category of design storms is based on the intensity-duration-frequency (IDF) curves of the Probable Maximum Precipitation (PMP) for the region of interest. These methods do not rely on average or probabilistic time-intensity distributions within rainfall events. Instead, hyetographs are designed to apply maximum depths (i.e., worst case scenarios) of rainfall based only on the frequency of occurrence for that depth and for a particular storm duration. Unfortunately, like the methods discussed in the first category, the probability or frequency of occurrence of the resulting runoff hydrographs are ambiguous and undefined.

Regardless of the specific method used to calculate runoff, the hydrographs produced by the IDF design storms are conservative, which makes them the preferred choice for design purposes. This is because they use PMP to create peak flows without considering the physical aspects of rainfall, infiltration, and runoff. Although these methods may result in conservative designs, they can bet cost effective because they may be more environmentally protective and because of their relative ease of use.

Koutsoyiannis (1994) described a fourth method, stochastic disaggregation, for creating design storms for the purposes of hydrological design. This method applies stochastic modeling techniques (i.e., a Markovian structure) to commonly used design storm methods or to other methods for determining runoff and flood routing. Stochastic disaggregation computes a probability distribution function of the outflow peak. This is a statistically more robust method for using design storms to provide information for hydrological design, regardless of the methods used to develop runoff hydrographs and route flows. Stochastic methods, such as those described by Koutsoyiannis (1994), are less likely to produce overly conservative designs, but they remain realistic in their physical and statistical analyses of precipitation inputs. Several stochastic models that use the methods outlined by Koutsoyiannis (1994) are available for personal computers. These programs typically run in conjunction with spreadsheets.

4.2 Losses from Precipitation

Infiltration, evapotranspiration, and surface storage are considered losses or "abstractions" from precipitation. A review of general procedures and information regarding precipitation losses is provided below, but a more detailed discussion of the methods used to measure each of these parameters is beyond the scope of this appendix. The reader is referred to Barfield et al. (1981) for a more complete discussion of these parameters as they are applied to mining.

Infiltration is the major source of precipitation loss. The physical processes controlling infiltration are complex and governed by a variety of interrelated factors. Particle-size distribution of the soil, porosity, antecedent moisture content, surface roughness, macroporosity, freeze-thaw cycles, and fluid properties all affect infiltration and each responds uniquely to storm intensity and duration. Field methods that are used to measure infiltration include double ring infiltrometers and rainfall simulators.

Several empirical methods are available to estimate infiltration. The most common of these are models by Green and Ampt (1911), Horton (1940), and Holtan (1961), and variations of these models. The original Green and Ampt model is commonly used by many computer hydrological models when adequate data are available to describe soil hydrological variables and antecedent moisture conditions. Barfield et al. (1981) indicated that for mining applications, the application of these methods is limited by the difficulty in measuring the physical parameters necessary for input. Accurate application also is confounded by the nonuniformity of soils, both spatially and with depth, and the high variability of all conditions across any watershed. It is important, therefore, that a hydrologist apply good professional judgment with well-founded assumptions when using these methods to estimate loss rates from precipitation. Wright-McLaughlin Engineers (1969) suggested that specific field tests were preferable and highly useful when making these estimates or applying professional judgment.

4.3 Surface Runoff

In the conceptual hydrodynamic model, excess precipitation is routed as overland flow to established channels and channel flow is routed to a basin outlet or a location of interest where a hydrological structure will be designed. Different methods can be used to develop and analyze the runoff hydrograph from data about precipitation excess and to route the flow down a channel or through a structure. In some cases, only the analysis of overland flow is required to design structures to protect or control runon of excess precipitation at a mine site. Methods commonly used to route flows through channels, detainment basins, or other hydrologic control structures are summarized in Section 4.4.

The method described by the SCS (1972) is the most common technique for estimating the volume of excess precipitation (i.e., runoff) after losses to infiltration and surface storage. The method involves estimating soil-types within a watershed and applying an appropriate runoff curve number to calculate the volume of excess precipitation for that soil and vegetation cover type. This method was developed for agricultural uses, and Van Zyl et al. (1988) suggested that it usually is not accurate enough for most design purposes at mine sites, primarily because the development and classification of runoff curve numbers by the SCS are imprecise. Curve numbers are approximate values that do not adequately distinguish the hydrologic conditions that occur on different range and forest sites and across different land uses for these sites.

A more appropriate technique for developing and analyzing runoff at mine sites utilizes the unit hydrograph approach. A unit hydrograph is a hydrograph of runoff resulting from a unit of rainfall excess that is distributed uniformly over a watershed or sub-basin in a specified duration of time (Barfield et al., 1981). Unit hydrographs are used to represent the runoff characteristics for particular basins. They are identified by the duration of precipitation excess that was used to generate them; for example, a 1-hour or a 20-minute unit hydrograph. The duration of excess precipitation, calculated from actual precipitation events or from design storms, is applied to a unit hydrograph to produce a runoff hydrograph representing a storm of that duration. For example, 2 hours of precipitation excess could be applied to a 2-hour unit hydrograph to produce an actual runoff hydrograph. This runoff volume can be used as input to route flows down a channel and through an outlet or for direct input to the design of a structure. Detailed procedures for developing unit or dimensionless hydrographs are presented in a variety of texts (Chow, 1964; Linsley et al., 1975; U.S. Bureau of Reclamation, 1977). The volume of runoff (i.e. precipitation excess) derived from an actual or design hyetograph is multiplied by the ordinates of the 1-inch unit hydrograph to produce a runoff hydrograph for a particular storm. Figure A-4 graphically demonstrates how a 1-inch unit hydrograph for duration D is used to produce a runoff hydrograph from 0.75 inches of precipitation excess of duration D. Figure A-5 demonstrates how a 1-inch unit hydrograph of duration D is used to develop a 0.7 inch runoff hydrograph by summing three components of excess precipitation from a complex storm with each component of duration D (Barfield et al., 1981). In this case individual runoff hydrographs are produced for each component of the storm using the 1-inch unit hydrograph. The hydrographs produced are lagged according to the duration of the components of the hyetograph as shown on the x-axis of Figure A-5. The individual runoff hydrographs produced are then summed to produce a 0.7 inch runoff hydrograph.

Common methods to develop and use unit hydrographs are described by Snyder (1938), Clark (1945), and SCS (1972). Unit hydrographs or average hydrographs can also be developed from actual stream flow runoff records for basins or sub-basins. The SCS (1972) method is perhaps the most commonly applied method to develop unit hydrographs and produce runoff hydrographs. The SCS (1972) publication recommended using the SCS Type I, Type I-A or Type II curves for creating design storms and using the curve number method to determine precipitation excess. Most mine site designs will require use of more rigorous techniques for determining precipitation excess than those proposed by SCS (1972).

Another technique to determine runoff from basins or sub-basins is the Kinematic Wave Method. This method applies the kinematic wave interpretation of the equations for motion (Linsley et al., 1975) to provide estimates of runoff from basins. A summary of the theory and the general application of this method for determining runoff is provided by the U.S. Army Corps of Engineers (1987) in outlining the operation of the HEC-1 computer software package. If applied correctly, the method can provide more accurate estimates of runoff than many of the unit hydrograph procedures described above, depending on the data available for the site. The method, however, requires detailed site knowledge and the use of several assumptions and good professional judgment in its application.

As previously indicated, only peak runoff rates for a given frequency of occurrence are used to design many smaller hydrologic facilities, such as conveyance features, road culverts, or diversion ditches around a mine operation. The hydrograph methods listed above can be used to obtain peak runoff rates, but other methods are often employed to provide quick, simple estimates of these values.

A common method to estimate peak runoff rates is the Rational Method. This method uses a formula to estimate peak runoff from a basin or watershed:

$$Q = C\,i\,A \qquad \text{(A-1)}$$

where Q is the peak runoff rate, C is a dimensionless coefficient, i is the rainfall intensity, and A is the drainage area of the basin. A comprehensive description of the method is given by the Water Pollution Control Federation (1969). The coefficient C is termed the runoff coefficient and is designed to represent factors such as interception, infiltration, surface detention, and antecedent soil moisture conditions. Use of a single coefficient to represent all of these dynamic and interrelated processes produces a result that can only be used as an approximation. Importantly, the method makes several inappropriate assumptions that do not apply to large basins or watersheds, including: (1) rainfall occurs uniformly over a drainage area, (2) the peak rate of runoff can be determined by averaging rainfall intensity over a time period equal to the time of concentration (t_c), where t_c is the time required for precipitation excess from the most remote point of the watershed to contribute to runoff at the measured point, and (3) the frequency of runoff is the same as the frequency of the rainfall used in the equation (i.e., no consideration is made for storage considerations or flow routing through a watershed) (Barfield et al., 1981). A detailed discussion of the potential problems and assumptions made by using this method has been outlined by McPherson (1969).

Other methods commonly used to estimate peak runoff are the SCS TR-20 (SCS, 1972) and SCS TR-55 methods (SCS, 1975). Like the Rational Method, these techniques are commonly used because of their simplicity. The SCS TR-55 method was primarily derived for use in urban situations and for the design of small detention basins. A major assumption of the method is that only runoff curve numbers are used to calculate excess precipitation. In effect, the watershed or sub-basin is represented by a uniform land use, soil type, and cover, which generally will not be true for most watersheds or sub-basins.

The Rational Method and the SCS methods generally lack the level of accuracy required to design most structures and compute a water balance at mine sites. This is because they employ a number of assumptions that are not well suited to large watersheds with variable conditions. However, these methods are commonly used because they are simple to apply and both Barfield et al. (1981) and Van Zyl et al. (1988) suggest that they are suitable for the design of small road culverts or non-critical catchments at mines. Van Zyl et al. (1988) suggested that the Rational Method can be used to design catchments of less than 5 to 10 acres.

It is important that the design engineer and the hydrologist exercise good professional judgment when choosing a method for determining runoff as discussed above. Techniques should be sufficiently robust to match the particular design criteria. It is particularly important that critical structures not be designed using runoff input estimates made by extrapolating an approximation, such as that produced by the Rational Method, to areas or situations where it is not appropriate. Robust methods that employ a site specific unit hydrograph or the Kinematic Wave Method will produce more accurate hydrological designs, but will be more time-

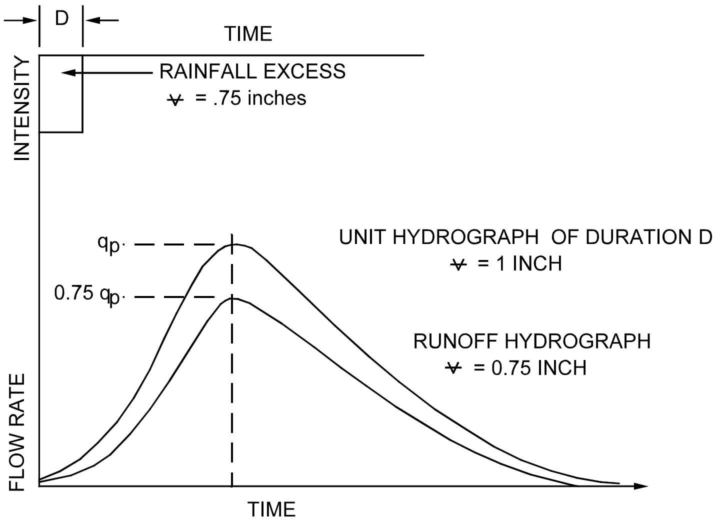


Figure A-4. Runoff Hydrograph Ordinates (y values) from rainfall Excess of Duration D Proportional to Ordinates of D-minute Unit Hydrograph (after Barfield et al.,1981).

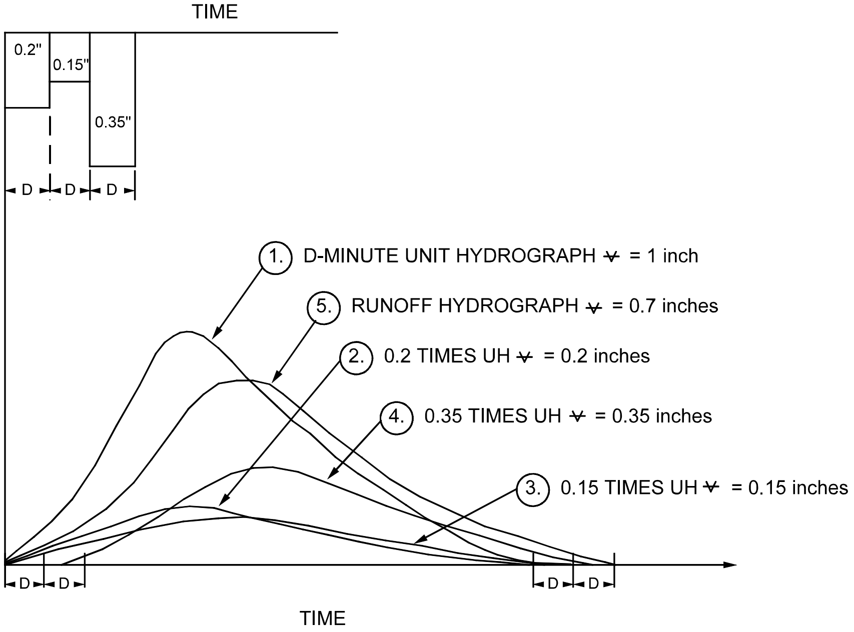


Figure A-5. Runoff hydrograph from a complex storm is obtained by summing the ordinates (y-values) of individual hydrographs from D-minute blocks of rainfall excess (Barfield et al., 1981). The hydrograph from each component of the complex storm of D duration is lagged by duration D, as shown on the x axis.

consuming to use. Nevertheless, many of the more robust methods have data requirements that often cannot be fulfilled because the available data are statistically inadequate. This may force a hydrologist to use their professional judgment to estimate input parameters or to use data that are not statistically adequate for their designs. Design and planning documents should describe the uncertainties associated with any assumptions or calculations, including those used to provide conservatism to the design. In general, EPA emphasizes that the method selected should be base don project objectives, and is prescribing no particular method in this document.

4.4 Stream Flow Routing

Designing hydrological structures or conducting water balance studies often requires an evaluation of the hydrologic inputs to the upper reaches or sub-basins of a watershed. As these flows are conveyed to the mine site, either in natural or constructed channels, their flow hydrographs are modified by travel time, channel storage, and the effects of influent and effluent reaches. Several methods are available to evaluate or study how flood flows are routed through a reservoir, a series of ponds, or an outflow structure. These techniques also can be used to design constructed channels.

Methods commonly used to route flows in channels are the Muskingum Method, a variant called the Muskingum-Cunge Method, the Modified Puls Method, and the Kinematic Wave Method. A detailed review of the general theory of flood routing and how each method solves or approximates the governing equation for continuity is beyond the scope of this appendix. The reader is referred to texts by Barfield et al.(1981) and Linsley et al.(1975) for more detailed discussions of how these methods are applied to mining. A summary of the theory and general application of these methods is also provided by the U.S. Army Corps of Engineers (1987) in their description of the HEC-1 computer software package.

The Kinematic Wave Method is a more robust technique that solves the continuity equation and, if applied correctly with appropriate data, can provide more accurate analyses of flood routing. As previously mentioned, this method requires the use of several assumptions and good professional judgment in its application.

4.5 Ground Water

Because most mine sites are located in regions with complex hydrogeologic conditions, a thorough understanding of the site hydrogeology is required to adequately characterize and evaluate potential impacts. Aquifer pump tests and drawdown tests of wells need to be conducted under steady-state or transient conditions to determine aquifer characteristics. If possible, it is important that these tests be performed at the pumping rates that would be used by a mining operation and for durations adequate to determine regional impacts from drawdown and potential changes in flow direction. These tests require prior installation of an appropriate network of observation wells. Transmissivities, storage coefficients and vertical and horizontal hydraulic conductivities can be calculated from properly designed pump tests. These measurements are necessary to determine the volume and rate of ground water discharge expected during mining operations and to evaluate environmental impacts. Tests should be performed for all aquifers at a mine site to ensure adequate characterization of the relationships between hydrostratigraphic units. Characterization studies should define the relationships between ground water and surface water, including identifying springs and seeps. Significant sources or sinks to the surface water system also need to be identified.

Hydrogeological characterizations should include geologic descriptions of the site and the region. Descriptions of rock types, intensity and depth of weathering, and the abundance and orientation of faults, fractures, and joints provide a basis for impact analysis and monitoring. Although difficult to evaluate, the hydrological effects of fractures, joints, and faults are especially important to distinguish. Water moves more easily through faults, fractures and dissolution zones, collectively termed secondary permeability, than through rock matrices. Secondary permeability can present significant problems for mining facility designs because it can result in a greater amount of ground water discharge than originally predicted. For example, faults that juxtapose rocks with greatly different hydrogeological properties can cause abrupt changes in flow characteristics that need to be incorporated into facility designs.

Computer modeling of surface and ground water flows is described in Section 6.0. The use of computer models has increased the accuracy of hydrogeological analyses and impact predictions and speeded solution of the complex mathematical relations through use of numerical solution methods. However, computer modeling has not changed the fundamental analytical equations used to characterize aquifers and determine ground water quantities. Traditional analytical calculations are briefly discussed below. The application of ground water modeling programs and analysis are discussed in Section 6.2.

A common method to analyze ground water in relation to a mine relies on a simple analytical solution in which the mine pit is approximated as a well. This method uses the constant-head Jacob-Lowman (1952) equation to calculate flow rates. Although not as sophisticated as a numerical (modeling) solution, this method gives a good approximation of the rate of water inflow to a proposed mine. It generally yields a conservative overestimate of the pumping rates required to dewater a mine (Hanna et al., 1994). A second method uses the technique of interfering wells, where each drift face of the proposed mine is considered to be a well. The cumulative production of the simulated wells is used to estimate the total influx into the mine and the extent of drawdown.

5.0 DEVELOPING A SITE WATER BALANCE

An accurate understanding of the site water balance is necessary to successfully manage storm runoff, stream flows, and point and non-point source pollutant discharges from a mine site. The water balance for typical mining operations will address process system and natural system waters (Van Zyl et al., 1988). Process system waters, which include make-up water, chemical reagent water, operational start-up water, water stored in waste piles, water retained in tailings, and mine waters (miscellaneous inflows), have reasonably constant and predictable flows over time. Natural system waters include rainfall, snowmelt, evaporation, and seeps and springs, which have variable and less predictable values (see Section 4.0). An overall site water balance superimposes these two systems to account for all waters at the site.

A mine site water balance must recognize that water may be stored in various facilities during mine operations. For example, in a heap leach operation, water is stored in the process ponds, the heap leach, and the ore itself. Water is lost from the system water through evaporation; facilities such as spray systems and process ponds may result in significant evaporative losses. Natural precipitation that falls on facilities such as heap leach pads or process ponds increases the total amount of water in the system as do any liquid chemical additives that are used in the processing of ore. During winter shutdown, or other temporary or permanent shutdowns, water collected in the facilities, including the ore itself, will drain and must be stored in the process ponds. In heap leach operations, the ore must be rinsed with water or chemical solutions to neutralize the environmental impacts of chemical reagents remaining in the ore (Van Zyl et al., 1988). For a tailings basin/milling type operation, inflows include tailings water, runoff, and other types of waters such as mine water that are often co-managed with tailings. Losses include water retained in tailings, seepage (to ground water beneath the tailings dam), pond evaporation, and recirculation waters.

A key aspect of the water balance at a site is the long-term variability of precipitation amount, intensity, and duration. Precipitation events can significantly change the estimated surface water and ground water volumes used in the water balance assessment. In turn, this can change the determination of whether a system will have a net gain or loss of water. For a mine with a gaining system, such as those in wetter climates, some type of a water disposal system may be required to achieve a balance. Typical disposal systems include evaporation ponds, surface outfalls, and ground water recharge systems. A mining operation with an overall losing system, as in dry climates, usually requires the input make-up water over time. A site with an overall losing system may still have a net gaining system for short times, such as during periods of high precipitation or snowmelt. Water disposal systems need to be designed to manage the water balance during these periods.

Process ponds should be sized to contain all water that would be in circulation during facility operations and during periods of temporary shutdown or rinsing and closure. A water balance is required to determine the sizes of these ponds (Van Zyl et al., 1988). In addition to holding the required volumes of process solutions, ponds must be able to accommodate additional water that flows into the system during extreme precipitation events.

Brown (1997) describes methods to determine a site water balance using both deterministic and probabilistic approaches. Deterministic water balances, similar to that described in Section 5.1, use set input values (e.g., average annual precipitation) to compute inflow and outflow. To provide insight into the range of conditions that could be expected to occur, deterministic water balances should be computed for average, wet, and dry conditions. In contrast, the input values used in probabilistic approaches are sampled from probability distributions (e.g., annual precipitation probability). Computer spreadsheets are used to iteratively calculate inflow and outflow probabilities. According to Brown (1997), probabilistic approaches result in better facility designs because they can indicate which parameters have the most effect on model results and may reveal potential design weaknesses.

5.1 Average Water Balance

The concept of an average water balance can be stated with the following mathematical formula:

$$S = I - O \qquad \text{(A-2)}$$

where S is the total storage requirement, and I and O are the sums of all inflows and outflows, respectively (Broughton and Tape, 1988). Using a cyanide heap leach operation as an example, the components of the average water balance are outlined as follows (Van Zyl et al., 1988):

<u>Water Balance Period (T)</u> - This is the period over which the average water balance components will be evaluated. The period must be long enough to include a complete leach rinse-cycle. On expanding ore pads, this period would equal the actual leach-rinse time. For a permanent pad, which may have several segments of ore that are either being leached, rinsed, or removed, the period would have to include a number of these cycles.

<u>Precipitation on the Ore and Pad (P)</u> - This is evaluated by multiplying the long-term average precipitation over period T by the total area contained within the berms around the leach pad.

<u>Evaporation from the Ore and Pad (E)</u> - Evaporation for the period T can be evaluated using either a factor multiplied by the Class A pan evaporation and the irrigated area at a particular time horizon, or using spray-loss graphs. Only the period during which actual leaching or rinsing occurs should be used when determining the pan evaporation.

<u>Rinse Water (R)</u> - Laboratory tests are usually required to determine the amount of rinsing water and reagents that must be applied to adequately clean the spent ore before disposal. Rinse-water volume may be as high as seven or eight pore volume displacements.

<u>Soil Storage (S)</u> - Soil moisture conditions vary in the heap during the ore placement, leaching, rinsing, and draindown periods. Each change in ore moisture results in water being taken up and stored in the pile or being drained from the pile into the ponds. Some of the water stored in the heap leach pile will not drain. Various moisture contents in a heap leach pile must be taken into consideration, including natural moisture content, agglomerated moisture content, field capacity or specific retention, and moisture content of the heap leach pile during leaching.

<u>Net Evaporation Loss from Pregnant and Barren Ponds (EP)</u> - This is calculated as the area of the ponds multiplied by the gross lake evaporation, minus the average precipitation over period T. In some cases, the evaporation rate may be modified by the water chemistry.

<u>Normal Operating Water Stored in Pregnant and Barren Ponds (SP)</u> - The ponds need to contain sufficient water to facilitate operation of the pump systems, as well as daily and weekly fluctuations in operating the system.

Water Stored in the Process Facility (SPR) - This volume is equal to the capacity of vessels contained in the process facility. It is generally very small and is included here for thoroughness.

Reagent Addition (RA) - This equals the amount of water added with the reagents used throughout the operating period T.

Bleed Water (BL) - This is the amount of barren bleed required to prevent the buildup of concentrations of certain constituents to values that are sufficiently high to interfere with mineral extraction.

After the above parameters are determined, the overall average water balance of the system, termed the balancing flow (BF), can be calculated as follows:

$$BF = P - E + R - EP - BL + RA - S \qquad \text{(A-3)}$$

Negative values of BF indicate that the system will require additional water, on average, equal to the amount of BF. Positive values indicate that water storage in the system will build up and excess water must be disposed.

5.2 Evaluating Pond Capacity

The water storage facilities at any site must be sized to contain the amount of water that would be in the system during a low probability, wet hydrological event (i.e. the worst-case scenario). Pond sizes should take into consideration the conditions that are likely to prevail during winter and total system shutdown, as appropriate. The conservativeness of the hydrologic event used in pond design depends on regulatory requirements, economic considerations such as the cost of additional pond capacity, the value of processed ore, and especially the environmental consequences caused by exceeding storage capacity.

During operations, process pond capacity should be evaluated monthly to measure fluctuations caused by changing precipitation and evaporation conditions. Performing monthly and quarterly evaluations permits close inspection of the operational aspects that may affect water storage requirements. Moreover, the monthly evaluation gives an indication of the critical or maximum storage capacity needed during any month.

The storage capacity of process ponds at a site typically is based on the worst-case climatic condition (i.e., a low-probability, high-flow event). In drier climates where, on average, the system operates with a large negative water balance, the critical duration of the design storm event usually is relatively short, varying from 1 to 60 days. During these events, the water system will show a net precipitation gain, thereby allowing the system to exceed storage capacity. In wetter climates, the critical duration is longer and may last over an entire season or over several wet years. Once again, it is prudent to consider a range of durations and choose the worst-case scenario (Van Zyl et al., 1988).

The critical duration design criterion is extremely important and should always be considered, even though such evaluations may be beyond the mandate of the regulatory requirements. If the critical duration evaluation is not used, the result may be unnecessarily conservative or dangerously overly optimistic pond sizing. The following two scenarios are examples from Van Zyl et al. (1988):

Overly Conservative Design - Assume the regulatory requirement prescribes a 6-hour probable maximum precipitation event (PMP) as the critical event. Water balance calculations indicate that the critical duration is 15 days. Analysis shows that the return period of the design event exceeds 1,000 years, which is considered overly conservative. Designing for this event means that there would be less than a 0.1 percent chance of overtopping a pond during any 1 year.

Liberal Design - Assume that the regulatory requirement prescribes a 24-hour, 100-year event as the critical design event. Furthermore, assume that the operation is located in a moderately wet climate and that the critical duration is actually 60 days. Analysis shows that the actual return period of the design event is less than 25 years. This means the chances that the pond will overtop exceed 4 percent each year. During a 20-year leach operation life, the probability of overtopping will exceed 80 percent. By most standards, this design would be deemed unacceptable.

In cases where critical duration analysis produces overly conservative or overly liberal designs, applicants should provide to regulatory agencies calculations disclosing the probability of overtopping for different critical durations as a part of their impact analysis. Further iterative design calculations may be warranted.

6.0 SURFACE WATER AND GROUND WATER MODELING

Mathematical models can be solved analytically or numerically. Either type of solution may involve the use of a computer. Analytical solutions are usually simple in concept and assume a homogeneous, porous media. Numerical solutions are usually more appropriate for complex, heterogeneous conditions. In general, models become more complex as fewer simplifying assumptions are used to describe a system or approximate a set of governing equations.

Anderson and Woessner (1992) suggest answering the following questions to determine the type and level of modeling effort needed:

- Is the model to be constructed for prediction or system interpretation, or is it a generic modeling exercise?
- What should be learned from the model? What questions do you want the model to answer?
- Is a modeling effort the best way to obtain the information required?

- Can an analytical model, rather than a more complex and labor intensive numerical model, be used to obtain a solution?

Answers to these questions will help the mining hydrologist to determine the methods to use to conduct a water balance study or design hydrological structures at a mine site. In addition, they will help to determine whether a solution should be analytical or numerical, steady state or transient, or, especially for ground water solutions, whether a modeling effort should be conducted in one-, two-, or three-dimensions (Anderson and Woessner, 1992).

Applicants will recognize that many ground water flow models assume porous media flow and may not replicate conditions at mines where rocks are intensely fractured. Modeling fracture flow may require applicants to collect additional data on the number, width, and interconnection of fractures (Anderson and Woessner, 1992). As described in detail in Anderson and Woessner (1992), fractured systems can be modeled by invoking conceptual models of equivalent porous medium, discrete fractures, or dual porosity. Each of these conceptual models uses assumptions that oversimplify flow through the fractured system. Consequently, applicants should exercise caution when interpreting the results of models developed in this manner.

6.1 Developing a Conceptual Site Model

A conceptual site model can be used to address the questions and evaluate the parameters discussed in Section 6.0. This model is a depiction, descriptive, pictorial, graphical, or otherwise, of the surface and subsurface hydrological systems, how they interact, and how they are related. The conceptual model should be developed concurrently with site characterization studies to determine important geologic formations, hydrostratigraphic units, and surface water interactions. A carefully constructed conceptual model will reveal important interrelationships that need to be evaluated, studied, or modeled. In addition, it will provide a basis for developing plans to monitor site conditions, analyze impacts, and construct numerical ground and surface water models. The conceptual model is usually simplified to consider only significant surface, subsurface, and interactive components because a complete reconstruction of actual field conditions is not feasible (Anderson and Woesner, 1992). It should be sufficiently complex to accurately depict system behavior and meet study objectives, but simple enough to allow timely and meaningful development of modeling or other analytical solutions.

The conceptual model provides a tool for identifying the questions to analyze using a mathematical model. Comparing the boundaries, dimensions, and input parameters of a particular mathematical model against the conceptual model, permits a user to evaluate the ability of the mathematical model to meet assessment needs. This type of comparison may indicate that specific components of the surface or subsurface hydrologic system cannot be simulated easily using a mathematical model. In this case, the conceptual model can be used to identify additional site characterization needs or model codes that are needed to accurately model specific components.

Conceptual model development begins by defining the area of interest and the boundary conditions of that area. Boundary conditions may include definitions of flow or hydraulic conditions across the boundary. The main steps in developing a conceptual model are to: (1)

define hydrostratigraphic units (these may or may not correspond to specific geologic units, depending on the degree of complexity required by the project objectives); (2) develop a general water budget that identifies sinks and sources to the system; and (3) define the type of flow systems to be studied or modeled.

6.2 Analytical Software for Surface Water Modeling

Most computer programs available to analyze surface water hydrology, perform watershed studies, and design hydrological structures are considered "analytical" software. Many of these programs use the algorithms discussed in Section 4.0 for analyzing precipitation, runoff, flow routing, and structure design. These programs allow a user to apply different algorithms to a particular problem and then compare the solutions. The output from one analysis, such as a watershed precipitation or snowmelt analysis, can be easily utilized by other routines to analyze runoff and route flows through a structure. One problem that can be associated with the use of empirical models (whether applied using a computer or by hand calculation) is that they are easy to misapply. As discussed in Section 4.0, it is important that the mining hydrologist understand the assumptions and approximations used by different methods and in what situations different methods are appropriate.

The U.S. Geological Survey has published a compendium on the use of surface water models (Burton, 1993). A complete review of this publication is beyond the scope of this report; however, the publication outlines recent research and application of surface water modeling techniques and the use of interactive spatial data systems, such as the use of satellite imagery and Geographical Information Systems.

Most analytical software used for hydrological analyses and structure design is available through the private sector. Some surface water hydrological, water quality, and groundwater software programs and models are available through the United States Geological Survey (USGS). Many of these programs and their manuals can be accessed and downloaded to a computer from the USGS via the internet (as of February 1999: water.usgs.gov/software). Brief descriptions of some of the more commonly used programs are provided below with particular emphasis on those that typically are used in mine settings.

HEC-1 Flood Hydrograph Package

HEC-1 (U.S. Army Corps of Engineers, 1987) is perhaps the most commonly used software for conducting watershed analyses and performing surface hydrological analyses for use in structure design and water balance studies. The program was originally developed in 1967 by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC). The program has been modified and improved throughout the years and a visual (graphical) version has recently been released.

HEC-1 generates hydrographs from rainfall and/or snowmelt, adds or diverts them, then routes the flow through stream reaches, reservoirs, and detention ponds. It models multiple stream and reservoir networks, and has dam failure simulation capabilities. The program can simulate level-pool routing for reservoirs and detention ponds. Figure A-6 outlines the techniques incorporated into HEC-1, many of which are discussed in Section 4.0.

TR-20 Project Formulation Hydrology

TR-20 (Soil Conservation Service, 1973) performs hydrograph generation, additions, or diversions, reach routing, or multiple pond network analyses. TR-20 uses the SCS methods to generate runoff hydrographs based on precipitation amounts specified for any storm duration. Hydrographs are computed using standard SCS Type I , IA, or II rainfall distributions, or other design hyetographs specified by the user.

HMR-52 Probable Maximum Storm

HMR-52 (Hansen et al., 1982) computes basin-average precipitation for Probable Maximum Storms and finds the spatially averaged Probable Maximum Precipitation (PMP) for a watershed. The PMP can be used directly with HEC-1 to compute runoff hydrographs for the Probable Maximum Flood (PMF) as the basis for dam spillway and failure analyses.

HECWRC Flood Flow Frequency

HECWRC performs a statistical analysis of historical stream flow data and plots the resulting flow-frequency curve. The program places both the observed and computed probability curves on the same plot. HECWRC uses the Log-Pearson Type III distribution as discussed in Section 4.0 to compute the return frequency curve.

HEC-RAS Water Surface Profiles

HEC-RAS (U.S. Army Corps of Engineers, 1991) software employs methods commonly used in open channel hydraulics and in the design and analysis of hydrologic structures. HEC-RAS computes water surface profiles for steady or gradually varied flow in natural or man-made channels. It handles subcritical and supercritical flows and can analyze the performance of culverts, weirs, and floodplain structures. HEC-RAS is used for evaluating flood hazard zones and designing man-made channels or channel improvements.

6.3 Numerical Modeling of Surface Water

A variety of software is available that combines analytical solutions with numerical modeling techniques to create watershed models. In general, these models employ finite-difference or finite-element techniques to route hydrographs and pollutants through surface-water systems. These models are particularly useful for evaluating the fate and transport of point and non-point sources of pollution through a watershed. Studies of this type could be used by mining

Overview of HEC-1 Computer Program
U.S. Army Corps of Engineers

Precipitation Analysis
- User Enters Time Intensity Distributions
- Any Distribution
- Any Duration
- Capable of Handling Multiple Stations

Infiltration Analysis
- SCS Curve Number
- Holtan Loss Rate
- Green and Ampt
- Initial and Uniform Loss Rate
- Exponential Loss Rate

Runoff Hydrograph Analysis
- SCS Unit Hydrograph
- Clark Unit Hydrograph
- Snyder Unit Hydrograph
- Kinematic Wave Method
- User Supplied Unit Hydrograph

Flow Routing
- Muskingum
- Muskingum-Cunge
- Modified Puls
- Working R & D
- Kinematic Wave

Other Features
- Reservoir Routing
- Dam Break Approximations
- Watershed Calibration
- Flood Damage Analysis
- Pumping Plants
- Diversions

Figure A-6. Summary of methodologies available in HEC-1.

operations to evaluate and model potential operational effects and releases in conjunction with the NPDES permit process. Two of the more commonly used models are described below.

Hydrologic Simulation Program FORTRAN (HSPF)

HSPF (Bicknell et al., 1997) is a set of computer codes that simulates the hydrologic and associated water quality processes on pervious and impervious land surfaces, in the soil profile, and in streams and well-mixed impoundments. The operational connection between the land surface and the instream simulation modules is accomplished through a network block of elements. Time series of runoff, sediment, and pollutant loadings generated on the land surface are passed to the receiving stream for subsequent transport and transformation simulation. Water quality and quantity can be evaluated along different segments or at outflow points within a watershed.

Water Erosion Prediction Project Hydrology Model (WEPP)

WEPP (Foster and Lane, 1987) is designed to use soil physical properties and meteorological and vegetation data to simulate surface runoff, soil evaporation, plant transpiration, unsaturated flow, and surface and subsurface drainage. The model uses the Green and Ampt infiltration equation to estimate the rate and volume of excess storm precipitation. Excess precipitation is routed downslope to estimate the overland flow hydrograph using the kinematic wave method. In WEPP, surface runoff is used to calculate rill erosion and runoff sediment transport capacity. The infiltration equation is linked with the evapotranspiration, drainage, and percolation components to maintain a continuous daily water balance for a watershed.

6.4 Analytical and Numerical Modeling of Ground Water

Ground water models are used in water balance studies at mine sites to evaluate and quantify ground water inflow to pits, channels, or other large structures associated with the mine. One-dimensional, vertical models may be used to evaluate situations where pond liners or other containment structures may have failed and knowledge of contaminant transport to natural ground water systems is required.

Most ground water modeling software is available through government agencies or the private sector. A thorough description of ground water modeling and the assumptions associated with its proper application is beyond the scope of this report. Instead, the reader is referred to the text by Anderson and Woessner (1992) for a detailed discussion of modeling techniques and applications and to a report produced by EPA in cooperation with the Department of Energy (DOE) and the Nuclear Regulatory Commission (NRC) that provides technical guidance regarding the development of modeling objectives, the development of site conceptual models, and the choice of models for use in particular problems (EPA, 1994). A brief description of ground water modeling and its application to mining is provided below. A description of some of the more common ground water modeling programs is also provided, with particular emphasis on those that are commonly used in mine settings.

Van der Heijde (1990a) defined a ground water model as the mathematical description of the processes active in a ground water system. Models vary in sophistication, with analytical solutions being the least complex and numerical methods, such as finite-difference or finite-element methods, being the most complex. A comparison of finite-difference and finite-element numerical methods is detailed by Pinder and Gray (1977). Both schemes are widely used to simulate transient flow in ground water aquifers (Freeze and Cherry, 1979).

Ground water models can be used to simulate heterogeneous systems in which a variety of coupled processes describe the hydrology, chemical transport, geochemistry, and biochemistry of near surface and deep aquifer systems. Ground water models may also incorporate the mathematical description of fluid flow and solute transport systems for both the saturated and unsaturated zones and take into consideration the complex nature of hydrogeological systems.

The predictive capabilities of ground water models depend on the quality of input data. The accuracy and efficiency of the simulation depend on the applicability of the assumptions and simplifications used in the model, the accurate use of process information, the accuracy of site characterization data, and the subjective decisions made by the modeler. Where precise aquifer and contaminant characteristics have been reasonably well established, ground water models may provide a viable, if not the only, method to adequately predict inflow to a mine pit, evaluate dewatering operations, conduct contaminant fate and transport studies, locate areas of potential environmental risk, identify pollution sources, and assess mining operational variables.

Ground water models can be classified into two broad categories. The first includes flow models that describe the hydraulic behavior of single or multiple fluids or fluid phases in porous or fractured media. The second category includes contaminant/chemical fate-and-transport models that analyze the movement, transformation, and degradation of chemicals in the subsurface. A detailed discussion of model classifications is presented by van der Heijde et al. (1985; 1988).

The modeling process consists of defining the problem, creating and calibrating the model, and conducting an analysis for a particular mining scenario or problem. Analysis of the water management problem in question is used to formulate modeling objectives and create simulation scenarios. Key elements of the problem definition step are conceptualizing the ground water system and analyzing and interpreting the existing data. Conceptualizing the ground water system includes: (1) identifying the hydraulic, thermal, chemical, and hydrogeologic characteristics of the system; (2) determining active factors such as pumping rates, artificial recharge, injection, or other anthropogenic factors, and passive factors, such as natural recharge, evaporation, and seep discharge; and (3) analyzing the level of uncertainty in the system (Kisiel and Duckstein, 1976).

The model calibration phase begins with the design of a computational grid that provides the basis for discretization of spatial parameters (van der Heijde, 1990a). Model calibration is accomplished by running iterative simulations, starting with field parameters and system stresses, followed by improving initial estimates based on the differences noted by comparing computed with observed values. As input parameters are continually refined, the model becomes more precise representation of the physical system.

After the model is calibrated to field conditions, it can be used to make predictive estimates. In this phase, different engineering designs, system alterations, or failure scenarios can be evaluated. Van der Heijde (1990a) suggests that uncertainty analyses should be conducted in conjunction with predictive modeling to assess the reliability of the simulation results.

During any modeling application, a lack of data can impede the efficiency of the simulation. Insufficient data can result from inadequate spatial data resolution, inadequate temporal sampling of time-dependent variables, and measurement errors. Van der Heijde (1990b) presents specific guidance on setting up quality assurance (QA) programs for ground water modeling studies. The major elements which should be incorporated into a QA program for modeling include:

- Formulate QA objectives and required quality level in terms of validity, uncertainty, accuracy, completeness, and comparability;
- Develop operational procedures and standards for performing adequate modeling studies; and
- Establish QA milestones for internal and external auditing and review procedures.

The QA plan should address collecting data, formulating the model, conducting sensitivity analyses, and pre-establishing guidelines for model calibration criteria. Ground water modeling for use in hydrologic design or water balance studies should incorporate a QA plan that addresses specific modeling objectives and the above parameters, depending on the risk associated with the specific design or study.

Commonly used programs for developing ground water models are briefly described below. These models were chosen to demonstrate the capabilities of some of the software available in the public domain.

AT123D

AT123D (Yeh, undated) uses analytical solutions for transient one-, two-, or three-dimensional transport in a homogeneous, anisotropic aquifer with uniform, stationary regional flow. The program allows for retardation and first-order decay when evaluating contaminant transport problems and permits simulation of a variety of source configurations, including point source, line source, and areal source inputs. It further allows the use of several boundary conditions to define flow parameters; longitudinal, horizontal and vertical transverse dispersion values can be input independently. The model calculates concentration distributions in space and time.

MODFLOW

MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) is perhaps the most commonly used software for creating ground water models and conducting predictive studies. MODFLOW is a numerical model that uses a finite-difference solution to solve the governing equations for ground water flow. It can be used to create two-dimensional areal or vertical models as well as quasi-three-dimensional or full three-dimensional models. Because of its numerical approach, it can be used to model transient flow or steady-state flow under anisotropic and layered aquifer conditions. Layers can be simulated as confined, unconfined, or convertible between the two conditions. The model can also handle layers that "pinch out". The model allows for analysis of external influences such as wells, areal recharge, drains, evapotranspiration, and interaction with surface water bodies such as streams. This software has been accepted for use by many regulatory programs.

FEMWATER/FEMWASTE

FEMWATER (Yeh, 1987) is a numerical model that uses a finite-element solution to solve the governing equations for ground water flow. It can be used to create two-dimensional areal or vertical models as well as full three-dimensional models in both saturated and unsaturated media. Because of its numerical approach, it can be used to model transient flow or steady-state flow under anisotropic and layered aquifer conditions. FEMWASTE is a two-dimensional transient model for the transport of dissolved constituents through porous media. The transport mechanisms include: convection, hydrodynamic dispersion, chemical sorption, and first-order decay. The waste transport model is compatible with the water flow model (FEMWATER) for predicting convective Darcy velocities in porous media that are partially saturated.

7.0 DATA REPRESENTATIVENESS

It is critically important to adequately understand the unique hydrology of a particular mine site. Mine sites may be situated in areas where precipitation rates vary significantly over a small area (e.g., due to orographic effects) or in remote areas for which meteorological records are lacking. In mountainous terrains, snowmelt and rain-on-snow events may produce large flow volumes that are difficult to quantify. These uncertainties make it difficult to characterize the entire hydrologic system.

Because the quality of field data available for mine sites may vary substantially, it is critical to know the advantages and limitations of the different methods that may be used to characterize site hydrology. As discussed in Section 4.3, the standard methods for predicting runoff must be used cautiously in mine site planning. The unique geographical and meteorological settings often encountered at mine sites mandate careful consideration of the assumptions used and require model results to be correlated with actual field data and conditions.

The nature of mining inevitably impacts the hydrology of a site, in terms of both water quantity and quality. Often, baseline hydrologic conditions are not well characterized because historical data either are unavailable or inadequate, or because the data have not been adequately evaluated. Preventing potential environmental impacts requires that a mine site's water system, both the natural and facility systems, be adequately evaluated. Evaluations of and conclusions concerning environmental impacts to site hydrology and water quality should be at least as precise and accurate as those of other economically important aspects of the project. For example, the studies, conclusions, and disclosure of potential hydrological and water quality impacts should be at least as accurate as those concerning the certainty and extent of the economic ore deposit.

The selection of appropriate statistical analysis techniques and the accuracy of their predictions are linked to data representativeness. Those statistical procedures whose assumptions best fit the population characteristics should be identified as the most appropriate data analysis procedures for use in baseline characterization and for design (Ward and McBride, 1986). In initial efforts to design a basic characterization or monitoring system, it is necessary to statistically analyze existing hydrological data and determine those characteristics that will influence the selection of data analysis procedures. If there are no existing data, data from a watershed presumed to be hydrologically similar should be obtained to provide initial estimates.

7.1 Statistical Concepts and Hydrological Variables

Basic descriptive statistical parameters for hydrological data include the mean, variance, skewness, and coefficient of variation. Statistical methods use hypotheses and tests to determine distributions, differences in parameters between objects, the significance of those differences, and confidence in the estimated values.

For many hydrological variables and environmental contaminants, the basic statistical assumptions of independent, normally distributed data are not realistic because environmental data commonly are correlated and non-normally distributed, with variance that may change over time (Gilbert, 1987). For hydrological and water quality data in particular, there are three commonly assumed parameters which may not apply to hydrological studies (Ward and Loftis, 1986): (1) independence of observations, including the absence of seasonality or serial dependence; (2) homogeneity of variance over the period of record; and (3) form of the probability distribution, (e.g., normal or non-normal). For these reasons, the statistical characterization of hydrological data for calculating mine water balances should include time series plots and testing for normality.

The many statistical techniques that can be used to characterize hydrological processes are presented in the references cited and will not be discussed herein. However, the following paragraphs present examples of two commonly used statistical methods for predicting components of a mine site water balance. Statistical techniques used for flood frequency analysis are presented in Section 4.0.

Linear regression is used to define the relationship between two variables whereas multiple regression is used to explain how one variable varies with changes in several variables. Analysis of Variance (ANOVA) can be used to determine the most or least significant variable. For example, single factor linear regression can determine the relationship of runoff volume to rainfall volume while multiple regression can determine the effect of multiple watershed characteristics (e.g., basin size or shape, stream length, stream density) on runoff peak discharges. Regression also can be used to analyze trends, provide information about flow and water quality differences, measure variance, and extend hydrological records from a gaged basin to an ungaged basin or stream.

Factor analysis can be used to evaluate complex relationships between a large number of variables and determine their separate and interactive effects. An example of factor analysis in hydrology would be to determine significant factors of importance in predicting watershed runoff, such as determining effects of basin size, shape, soil type, aspect, vegetation type, or other geomorphological factors.

7.2 Development of a Quality Assurance Program with Data Quality Objectives

The difference between the true value of a variable and the measured or calculated value is a measure of data quality. All hydrological data are subject to random errors, systematic errors including inconsistency and bias, and non-homogeneity. Random errors always are present in data. Inconsistency is the difference between observed values and true values while non-homogeneity reflects a changed condition that has taken place between sampling events. Predicting stream flows based on past properties of hydrologic variables requires that the conclusions be derived from data that are free of significant inconsistency and non-homogeneity, and with tolerable random errors (Yevjevich, 1972).

The amount of uncertainty that can be tolerated depends on the intended use of the data. The level of uncertainty that is acceptable is a critical part of the monitoring design (i.e., what, where, and how often to sample) and, therefore, must be incorporated into the sampling program. Statistical design criteria should be defined within any monitoring program. These criteria set limits on the confidence in the data by specifying the acceptable uncertainty in the estimated variables.

Gilbert (1987) identifies four categories of data validation procedures that should be performed:

(1) Routine checks made during the processing of data. Examples include looking for errors in identification codes (those indicating time, location of sampler, method of sampling, etc.), in computer processing procedures, or in data transmission.

(2) Tests for the internal consistency of a data set. These include plotting data for visual examination by an experienced analyst and testing for outliers.

(3) Comparing the current data set with historical data to check for consistency over time. Examples are visually comparing data sets against gross upper limits obtained from historical data sets, or testing for historical consistency using the control chart test.

(4) Tests to check for consistency with parallel data sets, i.e., data sets thought to be from the same population (i.e., from the same time period or similar stream). Three tests for consistency are the sign test, the Wilcoxon signed-ranks test, and the Wilcoxon rank sum test. These tests are discussed by Gilbert (1987).

Data reliability can be assessed using ANOVA to evaluate analytical, sampling (at a site), and regional (between sites) variability. If replicate samples have been collected, then an analysis of variance can determine whether there is a statistically significant difference between sources of variation. Basic assumptions for ANOVA tests include random samples, normal distributions and equal variances. ANOVA methods can help to focus additional sampling and aid data interpretation.

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