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Review and Evaluation of Paleohydrologic Methodologies

Prepared by M. G. Foley, D. A. Zimmerman, J. M. Doesburg,
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Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

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SUMMARY

Pacific Northwest Laboratory conducted a literature review to identify methodologies that could be used to interpret paleohydrologic environments. Paleohydrology is the study of past hydrologic systems or of the past behavior of an existing hydrologic system. The purpose of the review was to evaluate how well these methodologies could be applied to the siting of low-level radioactive waste facilities.

The computer literature search queried five bibliographical data bases containing over five million citations of technical journals, books, conference papers, and reports. Two data-base searches (United States Geological Survey--USGS) and a manual search were also conducted. As many of the identified publications as possible were collected, read, and analyzed to develop the lists of methodologies for synoptic, surface-water, and ground-water studies. The methodologies were examined for data requirements and sensitivity limits.

Paleohydrologic interpretations are uncertain because of the effects of time on hydrologic and geologic systems and because of the complexity of fluvial systems. Paleoflow determinations appear in many cases to be order-of-magnitude estimates. However, the methodologies identified in this report mitigate this uncertainty when used collectively as well as independently. That is, the data from individual methodologies can be compared or combined to corroborate hydrologic predictions. In this manner, paleohydrologic methodologies are viable tools to assist in evaluating the likely future hydrology of low-level radioactive waste sites.

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1.0 INTRODUCTION

Pacific Northwest Laboratory (PNL)[a] contracted with the Nuclear Regulatory Commission (NRC) to identify methodologies that can interpret paleohydrologic environments. Paleohydrology is the study of past hydrologic systems or of past behavior of an existing hydrologic system. Paleohydrologic studies are necessarily indirect because the original water in the system is gone. This report summarizes quantitative and semiquantitative techniques for estimating the past behavior of a hydrologic system. This past behavior could indicate a system's future behavior. Such an extrapolation may be as quantitative as an indirect discharge estimate of present floods, or as qualitative as an order-of-magnitude or bounding estimate of discharge, or of potentiometric surface elevation.

The objective of this study was to review the available literature and ongoing studies on paleohydrology and to evaluate the applicability and limitations of the various methodologies for siting near-surface disposal facilities for low-level radioactive waste. The methods reviewed were to apply to sites in the humid eastern United States as well as to arid sites in the western United States. Near-surface disposal facilities at these sites must (ref., 10CFR61) be located in the unsaturated zone, and must remain above the groundwater table for the period of isolation. Ground-water paleohydrologic methodologies can be used to gain confidence that water table fluctuations will not affect the facility. Surface water studies were also included in this report to provide methodologies for estimating the long-term behavior (500 years or more) of ungaged first-order streams near proposed sites.

This report bases the surface-water paleohydrologic techniques on the hydraulics of open-channel flow in alluvial channels; it bases the ground-water techniques on Oarcian flow through porous media as well as on stable and unstable isotope geochemistry of meteoric waters and transported materials. These methodologies apply to Quaternary flows of a million years ago and to flows that deposited sandstones now billions of years old, just as they apply to

(a) Operated by Battelle Memorial Institute yesterday's hydrology. The techniques are limited by the preservation of features related to flow parameters. Fewer data are available for older flows of interest, and features are usually preserved longer in arid climates than in humid ones. However, the fundamental paleohydrologic techniques are the same in all cases.

Although hydrology and climate are intimately related, paleoclimatology has not been included explicitly in this project. Such an undertaking would have been far beyond the scope of this study, and would have increased the amount of bibliographic material many times. However, paleoclimatic techniques cannot always be separated from paleohydrologic techniques, and have been included here when they are intimately connected to hydrologic methods.

This report begins with an explanation of the literature review itself. Methodologies for synoptic, surface-water, and ground-water paleohydrological studies are summarized and a synthesis of the individual techniques is discussed. A bibliography, including foreign language references, follows.

2.0 CONCLUSIONS AND RECOMMENDATIONS

Three general areas of paleohydrologic research provide useful techniques for estimating past hydrologic conditions relevant to the siting of low-level radioactive waste repositories. They are: 1) synoptic paleohydrology studies, 2) surface-water methodologies, and 3) ground-water methodologies. The techniques identified in each of these areas rely on empirical models or on quasi-deterministic models that combine known physical principles with empirical relations for estimating the values of hydrologic parameters of flows in past, present, or future hydrologic systems.

Synoptic paleohydrology studies use information that characterizes hydrologic conditions affecting a large geographical area. Remote sensing provides information on the color and albedo differences of the earth's surface; analysis of the imagery enables one to make inferences on the vegetation patterns, the underlying geologic structure, and the characteristics of surface paleochannels. Channel parameters amenable to analysis through remote sensing methods include channel dimensions, shape, pattern and sinuosity, gradient, and type of sediment being transported. Calculations of discharge, velocity, and sediment type can be made using empirical equations. Through these calculations, past hydrologic behavior can be inferred where adequate channel deposits are preserved, and thus future behavior relevant to the siting of near-surface disposal facilities can be extrapolated.

Surface-water paleohydrologic studies depend on the flexible, ad hoc application of open-channel flow hydrology to the estimation of paleoflows, and suffer from increasing degrees of uncertainty with decreasing knowledge of the paleoflow channel geometry and water surface profile. Estimates of paleoflows in existing channels with reliable high-water indicators and stable cross-sections have the least uncertainty, perhaps as little as a few percent in the most favorable cases. If high-water indicators are unreliable or missing, sediment initiation-of-motion criteria can be used in some cases to estimate flow depth, but such indicators may have uncertainties of more than 100 percent. Uncertainities of 100 percent or greater are also introduced when the paleochannel no longer exists, and its geometry must be estimated from sedimentological data. More sophisticated, computerized techniques are available for estimating flows in existing channels; however the sparse data available for most surface-water paleohydrologic studies seldom warrant the use of these methods. The use of several independent approaches can sometimes (depending again on the availability of data) indicate the range of uncertainty of the results.

Ground-water paleohydrologic techniques identified in this report fall into three groups. Techniques related to unstable isotopes use transport phenomena and decay times to determine residence time and travel time for ground water. Geochemical techniques can be used to determine the recharge area or the types of materials that a ground water has flowed through. Physical techniques demonstrate visible changes in materials that result from past action of ground water, and thereby indicate where the water table has been in the past. Most paleohydrologic studies use a combination of techniques to determine past conditions.

Almost all of the paleohydrological techniques discussed in this report are the result of ad hoc, informed application of technology from a variety of scientific disciplines to a particular problem often having an unusually abundant (relatively) data source. Thus, in its present state of development, paleohydrology is as much an art as a science and should be pursued by experts using multiple, independent approaches. For this reason, the approach we have taken in presenting paleohydrologic methodologies is to discuss what has been done in the context of as systematic a review of the relevant scientific principles as is possible or relevant. The result cannot be used as a handbook for paleohydrologic studies, but enough references have been included to guide the reader to more detailed approaches to specific problems.

3.0 THE LITERATURE REVIEW

The literature search began with a search of several computer data bases for references indexed by the key word "paleohydrology." Articles of apparent relevance to this review were obtained either from the PNL technical library or through interlibrary loans. Review of these articles suggested new descriptors or key words for use in a second computer search. At the same time, cited references in each article were used to explore for references not contained in the computer data bases. Also, a manual search of the Hanford Technical Library was performed to find additional references. Again, cited references from articles located in this search were checked to obtain new references.

As the volume of references and articles increased, identifying references already cited became difficult. To help keep track of the growing reference list, a computer data base, with a capability similar to the commercial data bases mentioned above, was developed to manage the bibliographic data. This facilitated organization and retrieval of specific information, prevented duplication of research, and eliminated many manual processes. The result was as thorough a search of the literature as could be devised, with an accurate and comprehensive accounting of every aspect of the search, and a system for managing the information that proved invaluable to the literature review itself.

THE COMPUTER SEARCH

Five bibliographical data bases containing over five million citations of technical journals, books, conference papers, reports, and theses of both national and international origin were searched:

- GEOREF — (1961 to present) covers all aspects of geology, geochemistry, geophysics, mineralogy, paleontology, petrology, and seismology.
- GEOARCHIVE — (1969 to present) covers the same fields as GEOREF.
- WRA — (Water Resource Abstracts) (1968 to present) covers all water-related aspects of the physical, life, and social sciences. Input to WRA is from selected institutions with active water research programs.

- DOE ENERGY (1974 to present) covers primarily energy topics--e.g., nuclear, geothermal, fossil, and tidal.
- SCISEARCH (1974 to 1977) covers technical and scientific literature of pure and applied science. It contains all the records published in the Science Citation Index.

In addition, two USGS computer data bases were searched for this task. In Reston, Virginia, a data base containing all the publications of the USGS was searched and the results were forwarded to PNL. The USGS office in Denver, Colorado, performed a computer search on a special data base containing articles dealing with the geology, geophysics, and hydrology in the vicinity of nuclear testing areas. Many records listed in that file are "for official use only," and are available only to government agencies and their prime contractors. Hence, these records are not listed in any of the publicly accessible data bases mentioned above.

A wealth of additional pertinent information could be obtained by examining the literature on paleoclimatology, which directly influences the paleohydrology. However, as discussed in the Introduction, this is beyond the scope of this task, and would have significantly increased the amount of information to be processed, perhaps by an order of magnitude. By applying restrictions, such as having the key word appear only in the title or only in the abstract, or by requiring only English language reports, the number of references actually extracted from the data bases amounted to less than 500. The foreign language articles could not be effectively reviewed in the time allotted, although the foreign language references are included in the bibliography. In all, over 400 references were extracted from the data bases; the articles obtained from this list served as a starting point for the literature review.

<u>THE MANUAL SEARCH</u>

To initiate this search, the printed references from the computer data bases were examined and appropriate articles were obtained. As each article was acquired, its bibliography was checked and new articles were sought. At the same time, three other searches were underway:

1. The card catalogue was searched for books or other publications containing relevant information. Subjects searched included paleo, ancient, hydrology, and hydraulic measurement.
2. A list of in-house journals was examined and those journals that appeared to have a reasonably good chance of containing relevant articles were selected. If a journal from this selection contained a yearly subject index, it was examined. Otherwise, when time permitted, the table of contents of the other journals were inspected. The list of journals with end-of-year subject indexes included: Water Resources Bulletin (1974-1980); Groundwater (1963-1969); American Journal of Science (1972-1980); Technology Review (1972-1975); and Remote Sensing and the Environment (1970-1980).
3. As the SCISEARCH (Science Citation Index) computer data base contained information only for the years 1973-1977, the periods 1961-1972 and 1978-1981 remained to be reviewed. Initially, the permuterm (subject) index was searched. Then, after accumulating several hundred references in the "paleohydrologic reference data base," several prominent authors in the field were identified. At this point, the source (author) index, which lists all the articles published by the author in each year, was searched.

From the list of 400-plus references obtained through the computer searches and the additional references obtained through the manual search, over 300 references were entered into our computerized bibliographic data base. References that appeared to contain significant relevant information were ordered through the Hanford Technical Library. As articles were received, they were reviewed to determine the general nature of their content (i.e., whether the techniques discussed pertained to surface-water techniques, ground-water techniques, or synoptic methods). The area of applicability for each reference reviewed was indicated in the bibliographic data base. This allowed all the references pertaining to a particular area of applicability to be extracted from the data base, assisting the literature review process.

THE BIBLIOGRAPHY

Many of the references in the data base were not ordered or were written in a foreign language, precluding a complete listing of the references by subject category (area of applicability). In addition, many articles contained information relevant to more than one area of applicability; hence, the bibliography is listed in alphabetical order by author.

The manual search for references in the Hanford library was complimented by searches in the University of Missouri, Columbia library and by searches in the University of Washington library. The Quaternary Research Library (University of Washington) was specifically targeted for paleohydrologic studies. The references collected were added to the bibliography and included where appropriate in the text of this report.

4.0 SYNOPTIC PALEOHYDROLOGY STUDIES

Synoptic paleohydrology studies, as used here, are empirical methodologies that yield data characterizing the hydrological conditions affecting a relatively large geographical area, or that depend on data averaged over a large area. These studies depend in part on remote sensing methods that provide improved perspective of the earth's surface. Other inputs to synoptic paleohydrologic studies come from areal field data on palynology, dendrochronology, and paleontology. Remote sensing of drainage basins provides qualitative information on past changes in hydrology (primarily surface waters) or imminent future changes. Remote sensing data combined with empirical observational data can provide semiquantitative estimates of the hydraulic properties of present or abandoned stream channels. Detailed chronological studies of areal vegetation distributions and growth rates can help relate effective precipitation to runoff, thereby providing an estimate of the recharge that was available for ground water in the past.

REMOTE SENSING METHODS

Remote sensing methodologies use reflected and emitted electromagnetic energy for producing spectral images of the earth's surface. Every object or material has unique properties that influence the reflection, absorption, and emission of different portions of the electromagnetic spectrum. The signature produced by these reflections and emissions can be correlated with the type of material. The most important advantage remote sensing offers is the synoptic view it provides of surficial patterns, shapes, and of differences in surface color and albedo (reflectivity).

The analysis of aerial and satellite imagery facilitates the recognition and mapping of subtle or poorly expressed hydrologic features that are difficult to identify by ground-based methods. The direct appearance on aerial or orbital photographs, or the specular reflection on other imagery, of vegetation and drainage patterns provides quantifiable information on the ground-water system recharge and discharge distributions (with appropriate ground truth). Vegetation patterns and type help identify shallow water-bearing zones. Seasonal variations in climate and foliage will significantly influence the photographic tones and vegetation patterns shown on the imagery. Also, the synoptic view of the surface aids in the characterization of landforms, the discrimination of mappable geologic units, and the delination of otherwise obscure lineaments, especially when aided by sophisticated computerized image analysis. More specific to this study, the topographic and geometric features depicted on the imagery provide data on the characteristics of surface paleochannels from which some hydraulic calculations can be made.

QUANTITATIVE RELATIONS (HYDRAULIC GEOMETRY)

Many empirical equations relating river discharge, sediment load, and channel shape and gradient use some areal parameters with values that can be determined more accurately from aerial photographs. For example, studies have shown that channel meander dimensions are related to the volume of water discharged through the channel, that channel dimensions and shape are related to the type of sediment load, and that channel gradient depends on past hydrologic conditions.

Dury (1965) found a relation between meander wavelength (L in feet) and bankfull discharge (Q_b in cfs) according to:

$$L = 30\ Q_b^{0.5} \quad . \qquad (4.1)$$

The scatter in the data used to develop this relation ranges over an order of magnitude and may reflect the influence of other variables. Schumm (1968) hypothesized that the type of sediment load moved through the channel has a significant influence on the meander wavelength. When the sediment load (expressed as the percentage of silt-clay exposed in the bed and banks of the channel, and defined as:

$$M = \frac{(M_b + W) + (M_b \cdot 2D)}{W + 2D} \quad , \qquad (4.2)$$

where

M_c = percentage of silt-clay taken from the floor of the channel,

M_b = percentage of silt-clay in the banks of the channel,

D = maximum bankfull depth, and

W = bankfull width of the channel)

is included in the regression analysis (Schumm 1968), an improved relation is obtained for both mean annual discharge (Qm in cfs) and mean annual flood (Qma in cfs) as:

$$L = 1890 \cdot \frac{Q_m^{0.34}}{M^{0.74}} \text{ , and} \tag{4.3}$$

$$L = 234 \cdot \frac{Q_{ma}^{0.48}}{M^{0.74}} \text{ .} \tag{4.4}$$

An estimate of the type of sediment load (M) can be inferred from the channel morphology and mode of sediment transport (Schumm 1977, pp. 155-156). Additionally, Schumm (1977) developed relations that demonstrated that both type of sediment load (M) and discharge (Q) have a determining influence on channel morphology according to:

$$W = 37 \cdot \frac{Q_m^{0.38}}{M^{0.74}} \text{ ,} \tag{4.5}$$

$$W = 2.3 \frac{Q_{ma}^{0.58}}{M^{0.37}} \text{ ,} \tag{4.6}$$

and

$$D = 0.59\, M^{0.34} \cdot Q_m^{0.29} \text{ ,} \tag{4.7}$$

and

$$D = 0.09\ M^{0.38}\ Q_{ma}^{0.42} \quad . \tag{4.8}$$

Bray (1973) formulated a relation between these same stream parameters and the discharge for a flood with a two-year recurrence interval (Q_2 in cfs) for gravel-fed streams in Alberta, Canada, as:

$$W = 2.38\ Q_2^{0.527} \text{, and} \tag{4.9}$$

$$D = 0.266\ Q_2^{0.333} \quad . \tag{4.10}$$

The channel depth and width in the above equations are the bankfull depth and width. Channel width can be determined from photographic tones, and vegetation and sediment patterns. The depth of dry channels can be determined using photogrammetric techniques.

The shape of stable alluvial stream channels, as expressed by the width-to-depth ratio (F), has been shown (Schumm 1977) to primarily depend on the silt-clay content (M) of the perimeter according to:

$$F = 115\ M^{-1.08} \quad . \tag{4.11}$$

Schumm combined the data on channel shape, silt-clay content, and discharge to derive the following equations:

$$F = 56\ \frac{Q_m^{0.10}}{M^{0.74}} \quad , \tag{4.12}$$

and

$$F = 21\ \frac{Q_m^{0.18}}{M^{0.74}} \quad . \tag{4.13}$$

River gradient depends primarily on the slope of the valley that was established by the river during times of possibly very different climatic and hydrologic conditions, and to a lesser degree on the type of sediment load and discharge moving through the modern channel (Schumm 1968). Schumm found that for stable alluvial rivers the channel gradient (Sc) could be related to the valley gradient (Sv), type of sediment load (M), and discharge (Q), according to:

$$S_c = 1.3 \frac{S_v^{0.94}}{M^{0.23} Q_m^{0.02}} \quad . \qquad (4.14)$$

Bray (1973) found that for rivers of Alberta, the channel gradient was related to the two-year recurrence interval flood and the median grain size (d_{50} in mm) according to:

$$S_c = 0.965\, Q_2^{-0.334} \cdot d_{50}^{\;0.58} \quad . \qquad (4.15)$$

Most of the above equations relate channel parameters to discharge; relations among channel parameters exclusive of discharge have also been established. Leopold and Wolman (1960) related meander wavelength (L) to channel width (W) and radius of curvature (R) according to:

$$L = 10.9 \cdot W^{1.01} \quad , \qquad (4.15)$$

and

$$L = 4.7 \cdot R^{0.98} \quad . \qquad (4.17)$$

Hack (1957) determined for streams in Maryland and Virginia that channel gradient is related to drainage basin area (A in square feet) and median grain size as:

$$S_c = 18 \frac{d_{50}}{A} \quad . \tag{4.18}$$

Discharge does not significantly influence the relation between sinuosity, the ratio of channel length to valley length, and the type of sediment load, because the sinuosity of a small stream can be nearly the same as that of a large river if the two are transporting similar types of sediment (Schumm 1968). Schumm found that for rivers of the Great Plains the sinuosity (P) is related to the channel's width-to-depth ratio (F) (Schumm 1963) and to the type of sediment load (M) (Schumm 1968) according to:

$$P = 3.5 \cdot F^{0.27} \quad , \tag{4.19}$$

and

$$P = 0.94\ M^{0.25} \quad . \tag{4.20}$$

The foregoing empirical formulae coupled with data from aerial photographs can be used to make hydraulic estimates in ungaged rivers or paleochannels. However, because of the complexity of the fluvial system and the variability in the data used to derive these formulas, discharge estimates based on these relations could at best give only an indication of the relative magnitude of the event.

REMOTE SENSING APPLICATIONS

Synoptic studies rely in large part on a combination of remote sensing and empirical modeling. For use in quantitative paleohydrology, uncertainties of synoptic studies can be order-of-magnitude unless a substantial data base is available, or unless specific ground-truth studies have been conducted. For example, a gravel pit centered on a paleochannel of the Murrumbidgee River, Australia, revealed deposits of cross-bedded sand that indicated the channel width was much larger than its surface expression as measured from aerial photographs (Schumm 1968).

A study of the Murrumbidgee River and its associated paleochannels (Schumm 1968) provided data for making paleoflow estimates. Methods of investigation included obtaining data from records at gaging stations, collecting and analyzing sediment samples, and taking measurements from aerial photographs. Radiocarbon dates of soil samples of 36,000 years (Pels 1964) and 28,000 years (Langford-Smith 1959) indicated a Pleistocene age for the paleochannels. Traces of paleochannels and the extent of the ancient flood plain were evidenced on the aerial photographs by meander scars and oxbow lakes. The width of the flood plains and the dimensions of the meander scars were much larger than the same dimensions of the modern Murrumbidgee River, indicating that past discharges were considerably larger than at present.

Schumm made crude estimates of water volume and sediments passing through the paleochannels. The Manning equation (refer to Section 5.0) was applied under the assumption that channel roughness and gradient were the same as the modern Murrumbidgee River. Bankfull discharge was calculated to be about five times greater than that in the Murrumbidgee River. Dury's equation [Equation (4.1)] relating bankfull discharge to meander wavelengths was applied using measurements taken from aerial photographs; discharge estimates were in agreement with estimates using Manning's equation. The sinuosity from the modern Murrumbidgee River and its paleochannels was plotted against the channel's width to depth ratio (F) and silt-clay content (M); the data conformed to the relations [Equations (4.19) and (4.20)] described earlier. The width-to-depth ratio versus silt-clay content relation also conformed to Schumm's relation, Equation (4.11).

Schumm concluded that the differences in the width-to-depth ratio and the channel sinuosity of the modern Murrumbidgee River and its paleochannels could be explained by a change in the sediment type, but that the change in channel dimensions (meander wavelength, channel width and depth) necessarily resulted from a change in discharge. Therefore, a major change in the hydrologic regimen of the system had occurred.

Holtz and Baker (1979) distinguished three major river types based on sinuosity and other parameters and used empirical formula to estimate their hydrologic properties from information obtained from photographs taken during the Apollo-Soyuz Test Project (ASTP) in 1975. The rivers were distinguishable by their size and morphology and were classified according to the environments of their drainage basins. Channel width, meander wavelength, and sinuosity measurements were taken from the photographs and used to calculate the width-to-depth ratio (F) and silt-clay content (M) according to Schumm's relations [Equations (4.19) and (4.20)]. The values calculated were used to indicate the general character of the rivers, not to make quantitative predictions. One reason for this caution was that these rivers are anastomosing in form in a tropical environment, unlike the single channel reaches in the semi-arid Great Plains where the empirical relations were derived. The sinuosity of the Jurura River, Brazil, was quantified from the ASTP photographs for the past and present. Abandoned channels and meander scars were used for making paleosinuosity estimates. Meander wavelength measurements were used to make discharge estimates using Dury's relation [Equation (4.1)]. However, a lack of field data for ground truth prevented verification. Of these estimates, Holtz and Baker found that Schumm's formulae [Equations (4.19) and (4.20)] were not always consistent with the photographic evidence because of the complex nature of bank resistance of tropical streams and because of a general lack of precise understanding of the behavior of tropical rivers.

Thomas and Benson (1970) demonstrated that streamflow characteristics can be related to basin characteristics through multiple regression techniques that extrapolate information at gaged sites to ungaged sites. Allord and Scarpace (1979) studied two basins in Wisconsin to see if LANDSAT imagery could be used to improve the equations developed to predict streamflow characteristics at ungaged sites. The LANDSAT images were analysed to provide land cover information. Land-use categories were classified as forest, grassland, water, wetland, mixed vegetation type, bare soil, and cropland. The spectral signatures of each class were determined from areas known to be representative of each land-use category. These signatures were used to classify the LANDSAT images into land-use categories and the data were used to develop relations for low flows and flood flows by the USGS method (Thomas and Benson 1970). Four of the nine basin characteristics determined from satellite imagery were significant variables in multiple regression techniques, whereas only

1 of 12 variables determined from topographic maps was significant. Estimates of the 7-day low flow at 2- and 10-year recurrence intervals were improved 17 to 20%. Similarly, flood frequency estimates for 10-, 50- and 100-year recurrence intervals were improved 45 to 50%.

The Mariner 9 (Baker 1981) and Viking missions returned photographic evidence of trough-like features on the Martian surface that are considered to be relict fluvial channels. The outflow channels display a variety of morphological features that also characterize the great Pleistocene flood channels that scoured through loess and basalt bedrock in the Channeled Scablands of eastern Washington (Baker 1971; Bretz 1969; Carr 1979).

A basic assumption of terrain analysis (Way 1978) is that landforms developing under similar conditions of age, weathering, climate, erosion, and relief will exhibit a characteristic set of visual and physical attributes, no matter where the landform is found. Also, recurrence of the landform implies a recurrence of the basic characteristics of the landform (i.e., soil and rock properties, topography, drainage pattern, ground-water conditions). On this premise, the features observed on the Martian surface are interpreted as having a fluvial origin.

Viking photographs of the Martian surface revealed a distinctive assemblage of channel landforms: anastomosing patterns, streamlined hills, inner channels with cataracts, pendant forms on the downcurrent side of flow obstacles, expanding and contracting reaches associated with flow constrictions, longitudinal grooves aligned parallel to fluid flow direction, and scour marks around obstacles. The only terrestial landscape that contains analogs to all the Martian outflow channel landforms is the Channeled Scablands of eastern Washington (Carr 1979). The common features include longitudinal grooves, teardrop-shaped (streamlined) islands, inner channel cataracts, terraced margins, and angular floor depressions. The lack of tributaries and the resemblance to the Channeled Scablands has led investigators to believe that the Martian channels were formed by catastrophic floods.

Estimates of discharge in some of the channels were made by applying the Chezy-Manning formula (refer to Section 5.0). The estimates of peak discharge in two Martian valleys ranged from 7×10^6 m^3/sec to 5×10^8 m^3/sec. Channel depths were estimated from shadow measurements or from evidence of flow around ejecta ramparts. Channel depth is only an indicator of maximum depth of water; hence, the estimates ranged over several orders of magnitude.

Carr (1979) proposed that the large channels were eroded by water released rapidly, under great pressure, from deeply buried aquifers. Carr's hypothesis suggested the following: The ancient porous near-surface rocks of the Martian surface acted as a sink for water in the planet's early history when climatic conditions were more temperate than at present. Subsequent global cooling sealed the ground water beneath a thick permafrost layer to form a system of confined aquifers. Episodic breakout from the confined aquifers under large artesian pressure formed the flood features. Carr estimated the discharge that could result under this hypothesis using the basic equation for ground-water flow in a confined aquifer (Deju 1971). Aquifer transmissivity was estimated by assuming a value representative of basaltic sequences on earth. Estimates of discharges for various aquifer thicknesses and chaos area (area where breakout was assumed to have occurred) ranged from 1×10^4 m^3/sec to 6.1×10^6 m^3/sec.

SUMMARY

Synoptic paleohydrology studies use information that characterizes hydrologic conditions affecting a large geographical area. Remote sensing provides information on the color and albedo differences of the earth's surface; analysis of the imagery enables one to make inferences on the vegetation patterns, the underlying geologic structure, and the characteristics of surface paleochannels. Channel parameters amenable to analysis through remote sensing methods include channel dimensions, shape, pattern (sinuosity), gradient, and type of sediment load. Calculations of discharge, velocity, and sediment type can be made using empirical equations. Through these calculations past hydrologic behavior can be inferred, and thus, future behavior relevant to the siting of near-surface disposal facilities can be extrapolated.

5.0 SURFACE-WATER METHODOLOGIES

Quantitative surface-water paleohydrology is analyzed by the same techniques used for analyzing the hydrology of existing streams. A method useful for determining the flow parameters of yesterday's flood in an ungaged stream is also applicable to the study of flows that occurred tens of thousands of years ago. The only difference is that the features that are the basis for determining flow parameters tend to become obliterated over time by slope development processes and continued fluvial erosion and deposition. These processes usually operate at faster rates in humid environments, resulting in an apparent bias toward arid environments in studies of older flows.

Methodologies useful for surface-water paleohydrology are based primarily on the hydraulics of flows in open, alluvial channels and on the sediment transport mechanics of open channels. Additional techniques, based on observational data, relate channel geometric parameters and have been discussed in Section 4.0 under the heading "hydraulic geometry." All methodologies are subject to uncertainty, the amount varying with the type of field data available and the complexity of the channel being studied. This section presents the physical basis of the hydraulics of flow and sediment transport in alluvial channels as a framework to discuss specific surface-water paleohydrologic methodologies, and discusses techniques for determining individual parameters and their relative uncertainties. These uncertainties can be reduced by the use of several, redundant approaches and by the use of combined methodologies that will be discussed at the end of this section.

MODELING

The study of flow in open, alluvial channels is extremely difficult in detail because the flows interact with the bed and banks to make a self-formed channel. Further, each channel is a historical record of past erosional and depositional events, and cannot be treated in detail by a generic physical model. Foley (1980a) discussed the analysis of such channels in terms of three classes of models, which are relevant to the entire field of paleohydrology:

"a deterministic class, in which known physical principles and initial and boundary conditions allow accurate description of system behavior; a stochastic class, in which systems are assumed to have inherent randomness and cannot be described by deterministic methods; and a parametric class, in which empirical relations among system variables may give some ability to predict system behavior."

Purely deterministic models of systems such as alluvial channels require overwhelming quantities of data (literally, every grain of sand), and have yet to be formulated. Parametric models, based on observations of field and laboratory channels, are the basis of "hydraulic geometry" methodologies (discussed in Section 4.0). These too require an overwhelming amount of data to have a model that can be applied to a specific channel; however, approximate applications are possible if the channel being analyzed is similar to the one observed. Uncertainties increase dramatically with increasing difference between properties of the observed and analyzed channels.

Foley (1980a) suggested that "a middle ground may exist between deterministic and parametric modeling, in which data-input requirements are minimized but output accuracy is compromised by use of lumped parameters whose details are unknown, but whose variability about some 'mean' may be estimated." Foley further suggested that such "quasi-deterministic" models may have some predictive capabilities outside the envelope of observed data that are lacking in parametric models.

FLUVIAL MODELS

The basis for hydraulic and sedimentological studies of alluvial, open channels of use in paleohydrology is a collection of quasi-deterministic flow and sediment-transport equations that rely on several lumped, empirical parameters. These contribute both to the ability of the models to address real hydrologic problems, and to the uncertainties inherent in those applications. The equations of general interest are those relating channel geometric parameters to flow resistance and amount, as these establish an analytical relation between variables of interest and ones with values that cab be determined in the field. Other empirical and quasi-deterministic relations between channel sediment properties and flow or geometric parameters will be discussed in more detail later in this section.

Shear Stress

An open-channel flow that does not vary with time (steady) or position along the channel (uniform) is such that the frictional resistance exerted by the channel periphery is balanced by the gravitational acceleration of the flow along the channel. It can be shown (Blatt et al. 1980) that this equilibrium requires that:

$$\tau_o = \rho g \frac{A}{P} \frac{h}{L} \ , \tag{5.1}$$

where τ_o is the average shear stress on the bed and banks, ρ is the density of the water, A is the cross-sectional area of the flow (see Figure 5.1), P is the wetted perimeter of the flow, and h is the drop along a length L of the channel. The ratio $\frac{A}{P}$ is usually referred to as r, the hydraulic radius. Channel slope $S = \frac{h}{\cos L}$ is approximately equal to $\frac{h}{L}$ for small channel inclinations, and the usual definition of τ_o for steady, uniform flow is:

$$\tau_o = \rho g r S \ . \tag{5.2}$$

Henderson (1966) has shown that, for nonuniform flow, S, must be replaced by the friction slope:

$$S_f = \frac{d}{dx}(h + \frac{V^2}{2g}) \ , \tag{5.3}$$

where x is the along-channel direction and V is the mean flow velocity in a cross-section, defined in relation to the flow volumetric discharge, Q, as:

$$V = \frac{Q}{A} \ . \tag{5.4}$$

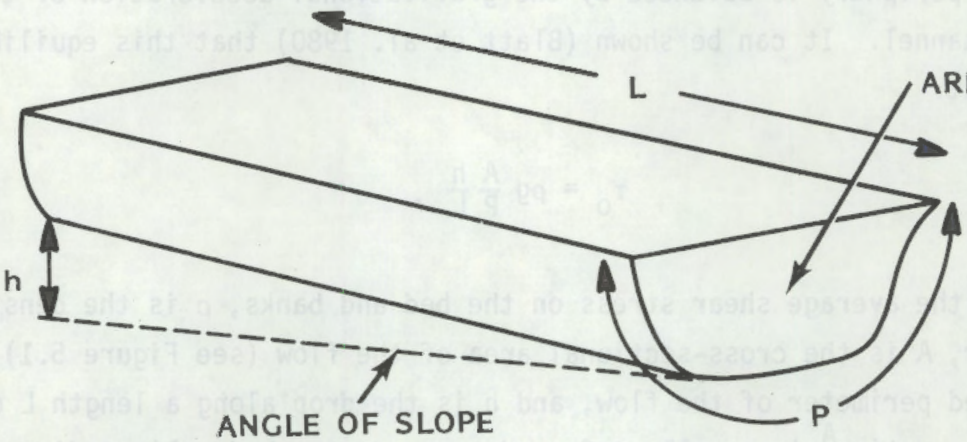

FIGURE 5.1. Definition Sketch, Flow in an Open Channel

The equilibrium-of-forces derivation of the equation for shear stress assumes that no nonfrictional energy losses occur in the flow. Flow separations around obstacles or at sudden expansions in the channel periphery, free overfalls, hydraulic jumps, and other energy losses will invalidate the above shear-stress relation, and must be avoided in reaches to be included in paleohydraulic analyses. Some special types of nonfrictional energy losses related to expanding channel reaches can be approximated, as will be discussed in a later section.

Discharge

The volumetric discharge, Q, or more commonly the equivalent mean cross-sectional velocity, V, can be expressed in terms of hydraulic and channel geometric parameters in the form of several semi-empirical equations. The two most widely used are the Manning equation and the Chezy equation. The Manning equation is:

$$V = \frac{1}{n} r^{\frac{2}{3}} S^{\frac{1}{2}} \quad , \tag{5.5}$$

where n is a dimensional, empirical frictional coefficient and all variables must be expressed in MKS units. Tables of empirical values for n may be found in texts on open channel flow (e.g., Henderson 1966), and vary from 0.025 to 0.150 for natural channels. The USGS (Barnes 1967) has published a well-illustrated report showing a variety of channels (different shapes, slopes, and sediment sizes) and their values of n determined by calculation from gaged velocities.

The Chezy equation

$$V = C(rS)^{\frac{1}{2}} \tag{5.6}$$

is also empirical, but is often presented with $C = (\frac{8g}{f})^{\frac{1}{2}}$ because that form,

$$V = (\frac{8grS}{f})^{\frac{1}{2}} \quad , \tag{5.7}$$

is the open-channel equivalent of the well-known Darcy-Weisbach pipe-flow equation. The resistance coefficient, f, known as the Darcy-Weisbach friction factor, is related to the roughness of the channel bed and banks and to flow parameters (Vanoni 1975).

Values for n (Limerinos 1970) and f (Brownlie 1981) can be determined from measured bed roughness in natural channels. However, in alluvial-channel applications, the bed roughness measured is often the median bed-sediment size. Even in a straight, uniform channel, the bed roughness is a function both of sediment roughness and bedform roughness. Studies have shown (e.g., Foley 1975) that the ratio of bed roughness, f, to flat-bed roughness, f', is:

$(\frac{f}{f'}) = 1$ for flat beds,

$1 \leq (\frac{f}{f'}) \leq 2$ for antidunes, and

$(\frac{f}{f'}) >> 2$ for ripples and dunes.

Specific methodologies discussed below address these relations in more detail.

QUANTIFYING INDIVIDUAL PARAMETERS

Paleohydrologic studies of surface waters are usually conducted for the purpose of estimating the maximum discharge (or maximum flow depth) that has occurred in a particular stream channel. Examination of the equations in the previous section shows that surface-water paleohydrologic methodologies stem from combined field and analytical techniques for determining the flow depth, width, cross-sectional shape, friction slope, and resistance coefficient. An additional goal of paleohydrologic studies is to establish the ages of prehistoric maximum flows to determine the statistical distribution of expected discharges in the current climatic regime, or to determine expected changes in peak discharges, which may result from a change to a pluvial or glacial climate.

Preservation of features that may be used to determine the values of these parameters is often serendipitous, and paleohydrologic investigations must necessarily be adapted to the specific field situation. For that reason, surface-water paleohydrologic investigations use flexible, ad hoc methodologies modified to suit the field problem. The flow equations discussed above provide the mathematical relations between parameters with values that may be determined by independent techniques and those for which no direct measurements are available.

Depth

Depth of flow in an existing channel or paleochannel is the most important parameter, in addition to the resistance coefficient, for calculating discharge. The accuracy of paleodischarge estimates for existing channels directly depends on the accuracy with which the paleodepths are determined or estimated. Techniques for determining or estimating paleodepth depend on the preservation of indicators of water-surface elevation or of sediments deposited in known relation to the water surface, or on less direct estimations that relate the competence of the flow to move large sediment to, among other parameters, the depth.

High-Water Marks

Benson and Dalrymple (1967) have discussed field techniques for indirect determinations of unmeasured stream discharge. An important aspect of these determinations is accurate measurement of high-water marks, and the techniques for identifying and evaluating indicators of water-surface level carry over into paleohydrologic studies. Floating debris deposited along the margins of a flow, "trim lines" dividing water-scoured banks below and unaffected banks above, and bent grass or other vegetation are principal indicators of water-surface elevation for studies of modern, ungaged flows.

These indicators of water-surface elevation can be affected by slope instabilities, which cause estimated elevations to be too low. They can also be affected by surge and superelevation. Marks on the upstream sides of obstacles will tend to be too high, whereas those on the downstream sides will be too low. Similarly, marks on the outsides of bends will be too high, whereas those on the insides will be too low. For these reasons, Benson and Dalrymple cautioned that high-water marks be measured preferentially in relatively straight channels on stable surfaces parallel to the flow.

Few of the techniques discussed above are useful in general in paleohydrologic studies because high-water marks are transitory features in all climates, and especially in humid ones. However, Stewart and Bodhaine (1961) were able to reconstruct stages for the 1815 and 1856 floods on the Skagit River, Washington, from high-water marks on trees and canyon walls and from suspended sediment lodged in tree bark and in crevices in canyon sides. The general requirements for representative indicators of water-surface elevation remain the same for paleohydrologic studies, and are the criteria for evaluating field observations. Paucity of data may require that data from less-desirable locations for high-water marks be used; Benson and Dalrymple's guidelines provide a basis for evaluating those data.

Ice-Rafted Debris

Although organic debris deposited during high-stage flows conceivably could be preserved long enough to be useful for paleohydrologic studies, the literature has provided no examples unassociated with slack-water sediment deposits (to be discussed below). Inorganic debris is more likely to be preserved, but usually does not float unless carried on or within floating ice. "Erratics" deposited from free-floating or grounded ice can provide excellent, long-lived markers. The highest erratics beyond glacial limits are usually accurate high-water marks if Benson and Dalrymple's evaluation criteria are met. Ice-rafted erratics provide a major source of high-water marks in studies of the Channeled Scablands of the Columbia Plateau (e.g., Fryxell and Cook 1964; Baker 1973). However, Baker (1973) pointed out that ice-rafted erratics in the Channeled Scablands were usually concentrated in areas where floodwaters were ponded, and are lacking in more uniform flood reaches where open-channel flow theory applies.

Eroded Channel Margins

The highest indication of erosion by a flood flow, or the highest base of a flood-cut scarp, is a minimum elevation for the water surface. For example, Bretz (1928) attempted to estimate flow depths of floods in the Channeled Scablands on the basis of scarps eroded in loess or on the highest scabland eroded in basalt. For paleohydrologic purposes, this analog of the trimlines used in estimating water-surface elevations for modern floods is of limited accuracy. In the case of Bretz's measurements, for example, it is known that the actual water surface was at least 60 m higher than the bases of the loess scarps (Baker 1973).

Minor Divide Crossings

For the catastrophic floods of the Columbia Plateau, Baker (1973) found that the most consistent measurements of water-surface elevation were provided by the elevations of the smallest channels eroded where flood waters topped the usual drainage divides. The water surface was bracketed between elevations of the floors of the minor channels and those of the lowest nearby divides unmodified by flood flows.

Highest Flood Gravel

Baker (1973) used the tops of flood-deposited gravel bars as indicators of minimum water-surface elevation. In the case of floods on the Columbia Plateau, these gravel bars were covered by flows of unknown depth and give water-surface elevations no more reliable than those indicated by eroded channel margins.

However, investigations in less-catastrophic floods have suggested that the highest flood gravels are not always unreliable indicators of water-surface elevation. For example, Stewart and LaMarche (1967) reported that the crests of natural, boulder-mantled levees formed during the flood of December 1964 on Coffee Creek, California, were up to 3 m above the channel bed and only 0.5 to 1 m below the flood high-water marks. Vessell (1977) found that the tops of some boulders up to 2.3 m in diameter deposited on levee or "boulder berm" crests in floods on the Rio Guacalate, Guatemala, were exposed above flood high-water marks. Vessell also found cobbles up to 20 cm in diameter deposited on a bridge deck approximately 4 m above the bed of the Rio Guacalate and very near the water-surface elevation of the flood reconstructed from conventional high-water marks discussed above.

The boulder berms on the Rio Guacalate were deposited in a diverging reach downstream of a flow constriction (Vessell et al. 1977). This suggests (Foley et al. 1978) that nonfrictional energy dissipation in the form of macroturbulent kolks (Matthes 1947) may have been the mechanism by which large boulders were deposited on the tops of the berms. Gary Parker suggested (written communication, 8 September 1978), based on laboratory experiments, that the boulder berms could have been formed by gravel-bar migration. However, Vessell (1977) showed that the boulders could have been transported in the deeper channels (necessary for entrainment by kolks) but not by the flows across the berm crests. Parker's observations may apply to formation of boulder berms in more uniform reaches, and may explain the formation of some of the bars observed by Stewart and La Marche (1967), Fahnestock (1963), and Scott and Gravlee (1968).

Foley et al. (1978) and Baker (1973) suggested that macroturbulent transport of boulders is most likely in diverging stream reaches where nonfrictional energy dissipation is important. For this reason, the water-surface elevations gained from observations of boulder berms, while more reliable than those from gravel bar elevations in more uniform stream reaches, are usually in flood reaches, which are less available for analysis, as described above. Thus, gravel deposits can be long-lived, desirable indicators of water-surface elevation. Additional uses of gravel deposits in paleohydrologic estimates will be discussed in later sections.

Slack-Water Deposits

Gravel and boulder deposits useful in reconstructing water-surface elevations depend on the supply of large sediment sizes to the paleoflows and on the ability of the paleoflows to transport the coarse sediments to potential sites of deposition. Further, as was discussed above, meaningful water-surface elevations derived from gravel deposits or boulder berms may require sediment transport mechanisms that are not operative on a large scale in the more uniform channel reaches suitable for analysis. Recent investigations (Patton, Baker and Kochel 1979; Kochel and Baker 1982) have used slack-water deposits--relatively fine-grained sediments that accumulate in areas of reduced flow velocity during floods--to estimate water-surface elevations of flood flows.

Kochel and Baker (1982) found that main-stem floods on streams in west Texas often follow flood peaks on tributaries, resulting in late-stage surges up the tributary valleys. These surges deposit the finer-grained detritus carried primarily as suspended load, and often cap such deposits with a layer rich in floating organic debris. If the slack-water deposits are preserved from erosion by floods on the tributaries, a layered sequence of deposits can accumulate with each layer representing deposits from a flood on the main stem that overtopped previous slack-water deposits. The organic cap typical of each deposit allows separation of sedimentation events and provides material suitable for radiocarbon dating.

As in the case of gravel bars, the slack-water deposits are covered by an unknown depth of water during deposition. However, by comparing water-surface estimates based on slack-water deposits with gaged data for floods on the lower Pecos River in 1954 and 1974, Kochel and Baker (1982) found that flow depth estimates were only about 10% too small. That is, slack-water sediment heights were usually 2 to 3 m below the water surface for peak flood stages of approximately 30 m. This relation between slack-water sediment elevation and peak flow elevation probably is a function of flood duration, suspended sediment size, and magnitude of the flood and would not apply to channels other than that of the lower Pecos without independent corroboration.

Evaluation

Discussions in the above descriptions of water-surface indicators have concentrated on the reliability and utility of each technique for paleohydraulic analyses. These range from very good for minor divide crossings and sediment lodged in canyon-wall crevices to qualitative for the bases of flood-cut scarps. These discussions have not addressed the relationship between the water-surface elevation of a paleoflow and its depth.

For a water-surface elevation for a paleoflow in an existing channel to be related to the flow depth, it must be assumed that: 1) the water-surface indicator be reliable as discussed above; 2) the present channel be representative of the channel during the flood, with no significant aggradation or degradation during or after; and 3) the water-surface indicator represents flows in the present channel. Significant degradation and aggradation of an alluvial-channel bed during flood-wave passage has been proposed by, for example, Leopold, Wolman and Miller (1964). However, Foley (1978) has shown that such behavior is probably not a problem in the relatively straight, uniform reaches that are most desirable for paleohydrologic analyses. The relationship of paleoflow high-water marks to the present channel can be more difficult to determine. For example, a water-surface indicator above stream terraces may simply indicate a flood that overtopped the terraces, or may suggest that significant channel incision has occurred since the flood that made it. In such a case (e.g., Foley 1980b), careful field mapping, interpretation, and historical reconstruction must be performed before the flow geometry can be determined from remaining evidence. This process is almost mandatory for work with Quaternary paleohydrology because enough time has elapsed so that the above assumptions are seldom valid.

Direct Depth Determination

Several techniques are available to estimate depth of flow directly from features of channel deposits. These are subject to more uncertainties for estimating water-surface elevation than the better of the techniques discussed above. However, depth-estimation techniques can add an independent check on water-surface determinations in which the relation between the paleochannel and present channel is not clear. Further, the depth-estimation techniques are useful in cases in which water-surface indicators are missing or where the bounds of the former channel are missing or questionable.

Competence Estimates. The maximum size of sediment particle that an open-channel flow can transport can be expressed as an empirical function of the shear stress (e.g., Vanoni 1975; Blatt et al. 1980). Typically, such relations provide a critical shear stress for initiation of motion of particles on a flat, alluvial bed composed of like-sized particles. Often, relations are further simplified by assuming that the particles have the same density of quartz and are immersed in water of 20°C. Baker (1973), Baker and Ritter (1975), and Foley (1977) have suggested that large particles (e.g., boulders) exposed on a bed of smaller particles are moved at lower shear stresses than predicted by common shear-stress criteria. Baker and Ritter (1975) derived an empirical relation for particle size versus mean shear stress for coarse bedload material transported in rivers which, when inverted and restated in consistent units (Foley 1980b), gives:

$$d = \frac{3.07}{\rho g S} d_{s_{max}}^{1.85} , \qquad (5.8)$$

where $d_{s_{max}}$ is the maximum sediment intermediate diameter and d and $d_{s_{max}}$ are in cm, ρ is in gm cm^{-3}, and g is in cm s^{-2}. John E. Costs (University of Denver, written communication dated 4 October 1982) has suggested that simple algebraic manipulation of Baker and Ritter's regression equation, as done by Foley (1980b) may give a different relation than generation of a separate regression equation using depth as the dependent variable and shear stress and particle size as independent variables. The effect of this different approach on Equation (5.8) has not been determined because it requires obtaining and replotting Baker and Ritter's original data and performing a new regression analysis, which could not be accomplished within the time available.

Use of Equation (5.8) to determine paleodepth assumes: 1) the boulders were transported as fluvial bedload, 2) the boulders sampled were the largest that the flow could transport, 3) the boulders were transported across a flat bed of generally smaller particles, and 4) the boulders sampled are in the same location in which they were deposited. Foley (1980b) used the above relation to estimate flow depths in an abandoned glacial outwash channel. To mitigate spurious determinations caused by ice-rafted debris, the $d_{s_{max}}$ used for each estimate was the average intermediate diameter of the ten largest boulders at locations beyond the former glacier margins. The sediment source was glacial debris, which assured a supply of boulders for transport by the stream of sizes large enough to assume that the largest were of the maximum size that the stream could carry. In studies of the Channeled Scablands (Baker 1973), this assumption cannot be made even for boulders of several meters diameter.

Theoretically more-reliable competence estimates can be made for the special case of coarse-facies segregates in deposits from antidune-regime flow. Flow regimes are discussed in more detail below. The important point here is that subregularly spaced clusters of coarse, sometimes imbricate, gravels in the deposits of steep streams transporting coarse bed materials are often relict antidune bedforms called transverse ribs (Rust and Gostin 1981) or bedload dropout armor (Foley 1977). Foley (1977) has shown in laboratory experiments that such deposits form from the largest bedload particles that a flow can transport by "normal" (i.e., not macroturbulent) fluvial processes over a flat bed by deposition on the upstream sides of growing antidunes. Thus, they demonstrate that all of the assumptions necessary for the use of competence estimates of paleodepth have been met. In addition, as is discussed below, the transverse ribs given an estimate of antidune wavelength that can be used in additional paleohydrologic estimates.

Competence estimates in the vicinity and upstream of morainal debris from Pleistocene valley glaciers require more care in field measurements. Leopold, Wolman and Miller (1964), Baker (1974), and Foley (1980b) have illustrated some of the care that must be exercised in field measurements of maximum fluvial boulder sizes in outwash deposits downstream of glacial moraines. Upstream of terminal moraines, maximum boulder sizes in stream channels can no longer be assumed to have been transported by fluvial processes. However, a plot of water-surface estimates made along a stream reach from all boulders larger than a given size may suggest a dividing line between a "normal" population (fluvial?) and "outliers" (residual glacial erractics?). Figure 5.2 shows such a plot for all boulders larger than 1 m in maximum diameter in a 40 m reach of the Middle Fork of the Popo Agie River, Wyoming (M. G. Foley 1979, unpublished data). Competence estimates were made using Baker and Ritter's (1975) equation, and the dividing line shown in Figure 5.2 could be interpreted as a maximum water-surface elevation. Further work would be necessary in any such application to lend credence to the separation of fluvially and glacially transported boulders. For example, the presence or absence of a lithologic difference between the "normal" and "outlier" populations could suggest differences in availability of particle sizes between the two lithologies for glacial transport rather than different transport mechanisms, and would require mapping of joint spacings in the source areas to choose between the alternate hypotheses.

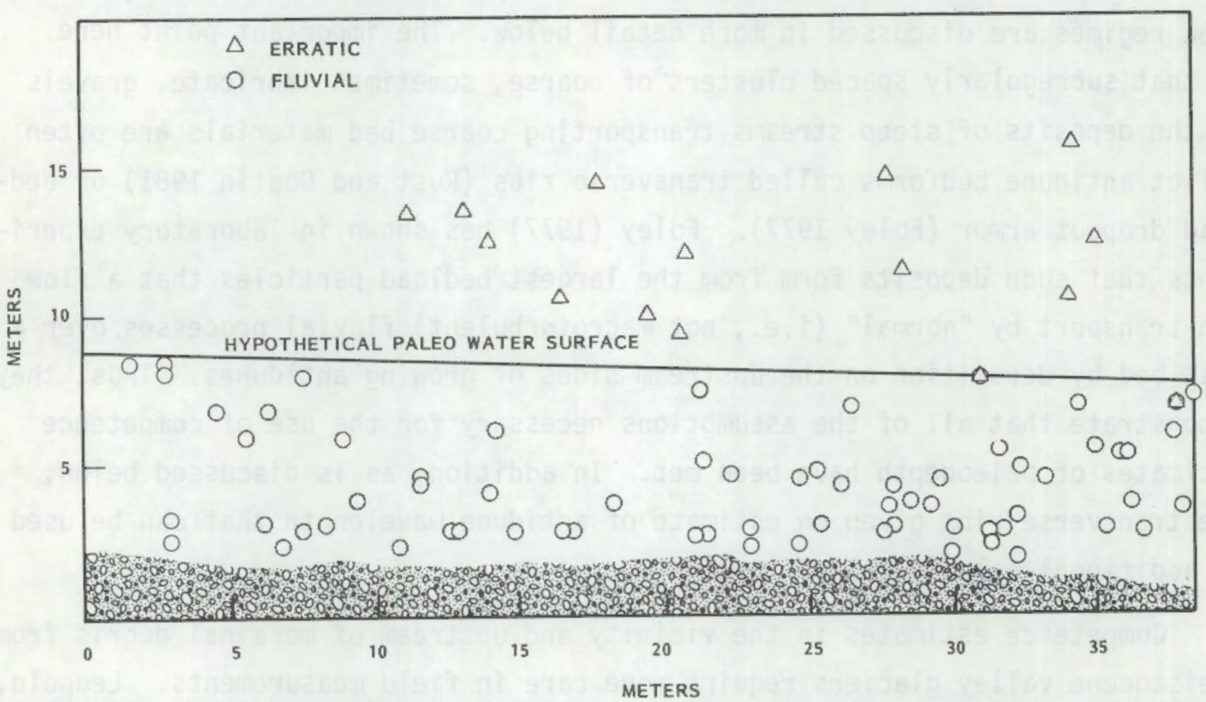

FIGURE 5.2. Estimation of Paleowater Surface in the Middle Fork of the Popo Agie River, Wyoming, by Calculating Paleodepths Competent to Move All Boulders Larger than 1 m Diameter Fluvially and by Discriminating Scattered Points (Glacial Erratics?) from Grouped Ones (Fluvial?)

Estimates from Antidune Geometry. The beds of alluvial streams are rarely flat, and depending on the velocity and depth of flow may be deformed into a variety of migrating bedforms (see Figure 5.3), beginning with an initial flat bed at very low flow, followed by ripples, dunes, high-sediment-transport flat bed, and antidunes as the flow velocity increases (Vanoni 1975; Blatt et al. 1980). Ripples and dunes migrate downstream and produce cross-laminations in the bed sediment that have only tenuous and poorly understood relations with flow depth and velocity, although they can be used for estimating other paleochannel parameters, as is shown below. However, antidunes have geometry (amplitude and wavelength) that is closely related to flow velocity and depth (Kennedy 1961; Vanoni 1975). Hand (1969) has suggested that antidunes can be represented as trochoidal waves, and has related their wavelength, amplitude, and maximum face slope to the mean water depth and amplitude of the accompanying water waves. This technique is promising, although antidune cross-laminae are not as common as those of ripples and dunes, and tend to be less regular or complete (Middleton 1965).

Evaluation. Except for the use of antidune cross-laminae, all of the above techniques depend on some variant of a critical shear-stress criterion for the maximum size of fluvially transported particle. This technique is at its best for large particles moved across beds of smaller ones when Baker and Ritter's criterion is used. Even then (Baker and Ritter 1975, Figure 1), shear stress (hence depth if slope is known) may be in error by as much as a factor of 7 for 10 cm cobbles, and by a factor of 2 for 1 m boulders. Baker and Ritter suggested that the effect of hydrodynamic lift was not considered explicitly in empirical determinations of critical shear stress. Thus, large particles (relative to those around them) in relatively shallow flows will have lift forces proportionately larger than in the experimental determinations, whereas those submerged in very deep flows with small velocity gradients will have proportionately smaller lift forces.

Foley (1980b) found that two water-surface elevations on the same cross-section determined from Baker and Ritter's relation differed by less than 4 cm for water depths of 1 and 2 m, This precision of 2 to 4% may have been

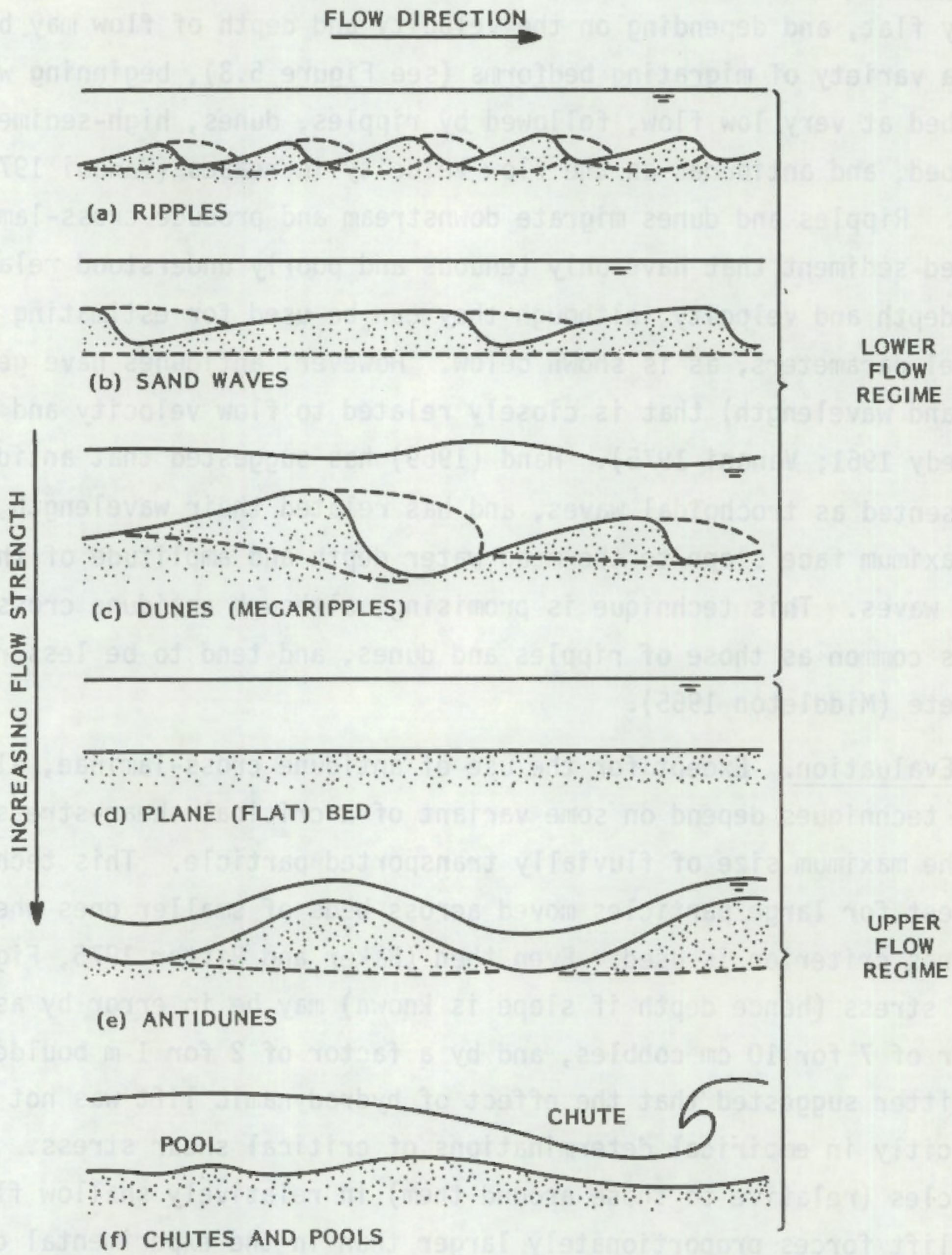

FIGURE 5.3. Types of Bedforms in Quasi-Equilibrium Unidirectional Flows. Dashed lines indicate zones of flow separation. Not to scale.

accidental, considering the relative crudity of the technique, and probably does not lend credibility to the accuracy of the method in general.

Helley (1969) derived a quasi-deterministic initiation-of-motion criterion for boulders on beds of smaller particles, based on hydrodynamic lift and drag, and tested it against field measurements. Helley considered that the boulders were tri-axial ellipsoids with intermediate axes inclined upstream between 0 and 25° (see Figure 5.4), short axes upward, and long axes horizontal and normal to the flow. Critical bottom velocities (i.e., at a distance of 0.63 times the short axis above the bed) calculated from the theoretical analysis and measured for 34 boulders in Blue Creek, California, were within 10% for 47.1% of the measurements, 11 to 20% for 23.5% of the measurements, 21 to 30% for 20.6% of the measurements, and greater than 30% for 8.8% of measurements. The details of the analysis are beyond the scope of this report. However, Helley's ignoring the geometric effects of upstream inclination of the intermediate axis results in a 24% error in calculated drag at an inclination angle of 25°. Further, it is not clear that the same velocity is appropriate for calculating lift and drag. Finally, although Helley's analytical technique holds promise for initiation-of-motion studies, the usefulness for paleohydrology is not as direct as criteria based on a critical shear stress. As is discussed below, estimation of the velocity profiles of sediment-laden flows is subject to great uncertainty. Thus, conversion of a relatively accurate critical bottom velocity based on Helley's analysis to a paleodepth or mean flow velocity may result in a potential order-of-magnitude error overall.

Slope

The methodologies discussed so far have assumed that the channel of interest is still in existence, and that water-surface or depth indicators (or both) allow reconstruction of the cross-section of the paleoflow. Two or more reconstructed cross-sections permit both the channel and water-surface slopes to be determined. The slope-area method, to be described below, is then used to calculate friction slope and paleodischarge. However, if the paleochannel has been destroyed, and paleohydrologic studies must be based on remnants of channel sediments, the determination of paleoslope is crucial to hydraulic calculations.

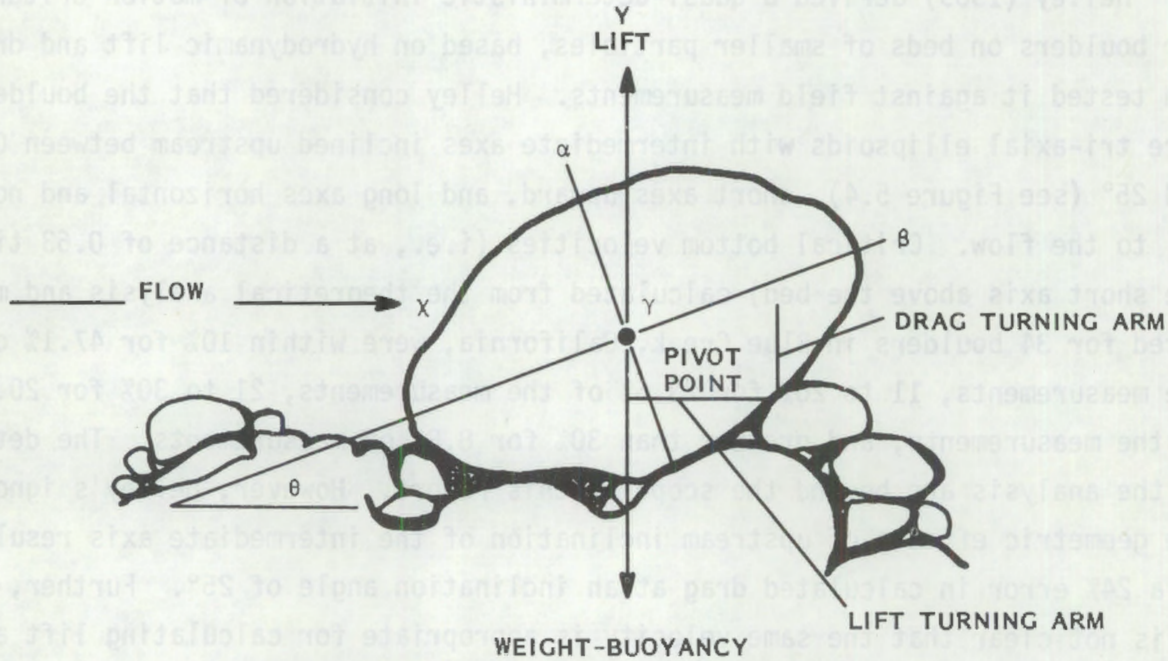

FIGURE 5.4. Orientation of Test Particles Placed on Bed of Blue Creek

The critical shear-stress criterion for movement of large sediment particles yields only the product dS when S is not known. Where transverse ribs are present, the wavelength of the antidunes that produced them is also preserved (Foley 1977; Rust and Gostin 1981). Kennedy (1961) has shown that the wavelength of antidunes is related to the mean flow velocity by the relation:

$$V = \left(\frac{gL}{2\pi}\right)^{\frac{1}{2}} \qquad (5.9)$$

Foley (1977) derived the relation:

$$d = 2.5\, k_s \, \exp\left[\left(\frac{V}{u_*} - a_r\right)\kappa\right] , \qquad (5.10)$$

where k_s is the bed roughness length, κ is von Karman's constant, a_r is a roughness coefficient (Bakhmetecff 1936), and

$$u_* = (\frac{\tau_o}{\rho})^{\frac{1}{2}} \quad (5.11)$$

These two equations may be solved simultaneously for d. However, the "constant" κ may vary from 0.2 to 0.4, depending on the concentration of suspended sediment in the flow (Vanoni 1975). A 10% error in κ results in a 100% error in d as determined by this method, suggesting that it should be used for order-of-magnitude calculations only (Foley 1977). However, Coleman (1981) has suggested, based on his experiments, that earlier findings were in error, and that the value of κ is independent of the amount of suspended sediment in open channel flow. Evaluation of Coleman's findings may prove that the technique suggested by Foley (1977) is subject to less inherent error caused by variable κ than had been suspected previously.

Other techniques for determining paleoslope require the estimation of former valley cross-sections from the geometry of tributary streams or preserved remnants of peripheral parts of the former valley. Matthes (1930), in his classical study of the Yosemite Valley, reconstructed multiple Pleistocene positions of the Merced River by projecting the profiles of tributary streams in hanging valleys across the Yosemite Valley. Multiple reconstructions were possible because several graded tributary profiles were preserved between knickpoints in the bedrock hanging valleys. Foley (1980b) used remnants preserved under glacial till to reconstruct a valley profile at the time of diversion of the Dearborn River, Montana, and a later profile projected from valley remnants buried by a younger till. These techniques clearly suffer from the uncertainty associated with the projection of curvilinear features over distances of a kilometer or more. However, several determinations made along a reach of tens of kilometers should mitigate the effects of local errors.

Width

The cross-section of a paleoflow in an existing channel can be determined by surveying the channel and estimating the flow depth somewhere along that cross-section as described above. Uncertainty is introduced by post-flow changes in the banks, such as slumping and landsliding or deposition of near-bank colluvial material. Further uncertainty can result from superelevation of flows in curved reaches. However, these uncertainties can be avoided by careful selection of cross-sections in relatively straight reaches away from areas of post-flow erosional or depositional activity.

However, when the paleochannel is missing, or as in the case of the Missoula floods, was ill-defined when active, a quantitative estimate of paleowidth is difficult and subject to large uncertainties. Schumm (1968) estimated the widths (and bankfull depths) of buried prior stream channels of the Murrumbidgee River in Australia from detailed cross-channel stratigraphy (Figure 5.5).

Cotter (1971) estimated the width and depth of channels in which sands of the Late Cretaceous Ferron Sandstone were deposited using stratigraphic and textural data. Cotter assumed (based on Moody-Stuart 1966) that bankfull depth in the meander bends was equal to the thickness of the intervals of epsilon cross-stratified point bar sandstones. Further (also based on Moody-Stuart 1966), he estimated paleochannel width as 1.5 times the width of the point bar sandstone. Cotter then "adjusted" paleochannel depth downward somewhat to describe the depth of a straight reach, and derived a width-depth ratio of 12 for the straight paleochannel. This value compared with a width-depth ratio of 8 determined by measuring the silt-clay content of the "bed" and "banks" in thin-section and using Schumm's (1960) relation for alluvial channel geometry as a function of sediment type.

The 50% discrepancy between Cotter's (1971) width-depth ratios calculated by independent methods is probably a good indication of the uncertainty of paleowidth determinations. Cotter's direct estimate of width may have been in error by tens of percent. His direct estimate of depth would have had a similar uncertainty, although the use, when possible, of the more accurate techniques described in a previous section could have reduced that uncertainty. In addition, the estimates of silt-clay contents of the bed and banks could have been affected by the formation of authigenic quartz on the sand grains and of diagenetic clay by weathering of feldspars and mafic detrital grains. Schumm's (1960) hydraulic geometry relation depends on the detrital silt-clay

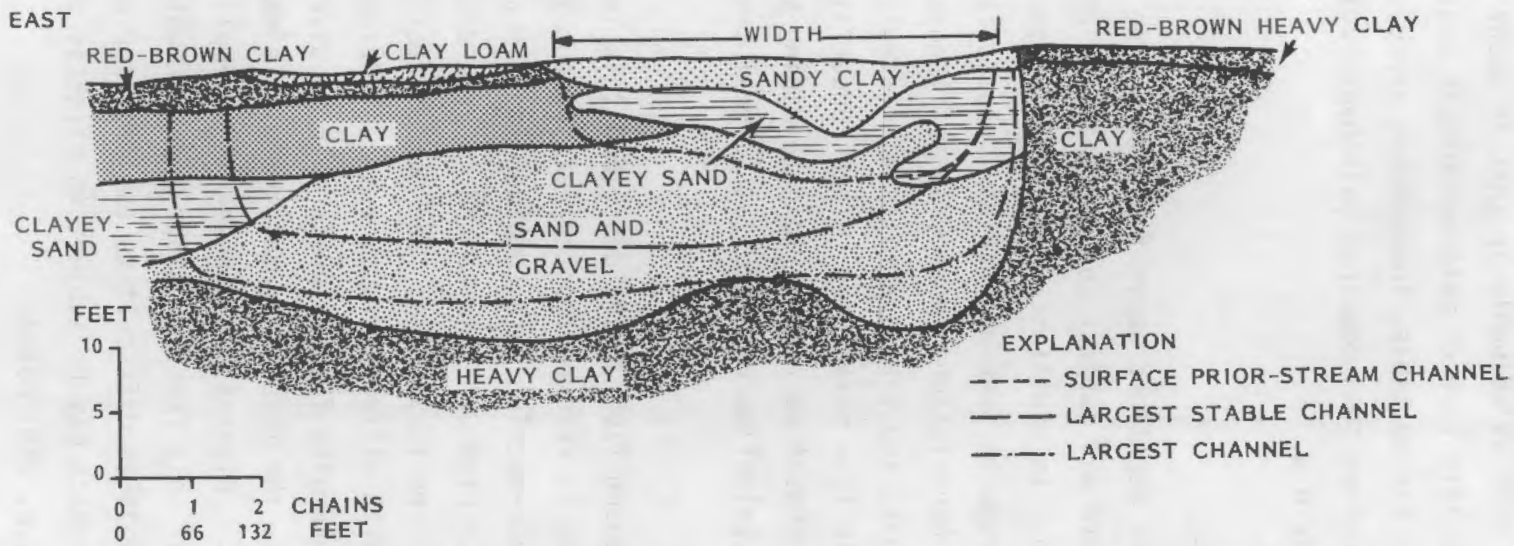

FIGURE 5.5. Generalized Cross-Section of Prior Stream Channel

content and can be reasonably accurate (Foley 1975), but would be seriously affected by changes in silt-clay content induced by secondary mineralization.

Cotter's (1971) work is valuable in that it quantifies the uncertainty associated with a specific type of paleohydrologic analysis, and also demonstrates the necessity for multiple, independent approaches to paleohydrology. The next section describes some combined paleohydrologic techniques and gives some examples of their use.

COMBINED METHODOLOGIES

The methodologies described above for determining the paleovalues of hydraulic variables are all subject to uncertainties of varying magnitudes, as has been discussed. In addition, application of the flow equations to natural channels introduces some uncertainty because real, self-formed channels are seldom uniform. Nonfrictional energy losses induced by changes of channel shape, flow separations, and free overfalls will result in smaller discharge for the same geometric flow parameters. These uncertainties may be reduced by using multiple, independent approaches to determining values of hydraulic parameters and by making paleoflow estimates at several cross-sections.

Slope-Area Method

Dalrymple and Benson (1967) have described this technique in excellent detail, and the reader is referred to their treatment for actual application. In brief, several cross-sections are combined in this approach and treated with the Manning equation. High-water marks and in situ determinations of roughness coefficient are necessary input data. Each cross-section may be divided into several subsections with different roughness coefficients, and flow may be nonuniform (although converging flow is preferable to diverging flow). Given good high-water marks, the major uncertainty in this method is the estimate of roughness coefficient. Riggs (1976) presented a simplified slope-area method that requires input of only friction slope and high-water marks. Overall accuracy of these two methods is difficult to estimate for an ungaged site, although Riggs' simplified approach may be subject to slightly greater uncertainty. However, Riggs (1976, p. 285) noted:

"Opinions range from claims of high accuracy to the comment of a prominent (unnamed) hydraulic engineer who was quoted by Henry Beckman (written communication 1924) as saying that, whenever results obtained by the slope-area method came nearer than 25 percent to the correct result, it was due either to accident or to a second choice of factors to use in the formula after the first choice had gone amiss. Fifty years later, wide differences of opinion as to the accuracy of the method still exist."

Despite differing opinions concerning its uncertainty, where data of sufficient quantity and accuracy are available the slope-area method is probably the most sophisticated technique of real use in most paleohydrologic studies. It is the basis for Baker's (1973) paleohydrologic studies of the Channeled Scablands and Vessell's (1977) study of the Rio Guacalate. In addition, it is often used in studies of maximum flood discharges in ungaged streams, or in rivers with gages that were destroyed by floods.

Other Combined Methodologies

Modern river studies employ more sophisticated techniques than those described above. Examples are the step-backwater analysis (Sherman 1976) and other computerized models such as HEC-2 (U.S. Army 1973). However, most paleohydrologic studies are data-limited, and the less-sophisticated techniques described above are adequate.

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6.0 GROUND-WATER METHODOLOGIES

Ground-water studies are based on two different, but related, foundations: the sciences of geology, and the sciences of chemistry, physics, and mathematics. The hydrologist must understand geologic environments to understand the geologic influences on ground-water flow. He must also have a clear grasp of pnysics and chemistry to quantitatively examine ground-water flow, and of mathematics to provide a language that can describe the scientific observations.

Ground water as a science is usually traced to the work of a French hydraulic engineer named Henry Darcy. He developed an empirical law (Darcy's Law) which states that the velocity (v) of a fluid through a uniform, porous medium is defined by the following equation:

$$v = -K\frac{\Delta h}{\Delta \ell} , \qquad (6.1)$$

where h = hydraulic head ,

ℓ = length , and

K = hydraulic conductivity.

K is a function of the medium and of the fluid flowing through it. Darcy's Law can be modified to describe the discharge, Q, of a given system:

$$Q = -KiA , \qquad (6.2)$$

where i = hydraulic gradient ,

K = hydraulic conductivity , and

A = area.

As previously stated, Darcy's Law is empirically derived. Other researchers relied more on the analysis of physical processes to understand ground-water flow. For example, Hubbert (Freeze and Cherry 1979) defined potential as "a physical quantity, capable of measurement at every point in a flow system, whose properties are such that flow always occurs from regions in which the quantity has higher values to those in which it has lower, regardless of the direction in space." This definition can be condensed to: the fluid potential (Φ) is equal to mechanical energy per unit mass of fluid:

$$\Phi = gz + \frac{v^2}{2} + \int_{p_0}^{p} \frac{dp}{\rho} \quad , \tag{6.3}$$

where g = acceleration of gravity ,

z = elevation ,

v = velocity ,

p = pressure , and

ρ = density of the fluid.

This potential is the sum of the work required to accelerate the fluid from zero velocity to velocity = v, and the work required to induce the fluid pressure. Given an incompressible fluid, and by substituting terms, we can derive the relation:

$$\Phi = gh \cdot \tag{6.4}$$

In incompressible fluids of uniform density, fluid potential and hydraulic head are almost perfectly correlated.

The calculation for fluid flow must be coupled to the physical properties of the fluid flow and porous medium to describe the hydraulic aspects of ground-water flow. Given just six properties: density, viscosity, and compressibility for the fluid; and porosity, permeability and compressibility for the medium; all other parameters can be derived. This report is not designed to discuss the various methods by which properties such as specific storage, transmissivity, and storativity can be calculated, but rather is designed to discuss how the physical parameters can be used to enhance knowledge and understanding of a given system.

As in the case of surface-water paleohydrology, the technical foundations of the hydrology of contemporary ground-water systems must be applied to ground-water paleohydrology. If we can apply the formula of fluid transport in a ground-water system to a real data set, we may be able to better understand the evolution of that system and to predict its future. To do this, we should imagine a "typical" ground-water system. This system (Figure 6.1) consists of a land surface where rainfall enters the soil; a vadose or unsaturated zone where water percolates through to the water table; an unconfined aquifer; and a confined aquifer. Numerous physical parameters are measurable throughout the system. Isotopes and various chemical species are in the ground water and the air, and these same species are in the water in the atmosphere and the ocean. A relation exists between the concentrations of these species and time, and relations exist between parent and daughter isotopes. Interactions take place between the water, material, and medium as the water moves through the hydrologic cycle carrying these various isotopes and chemicals. From the relationships of these interactions we can develop an understanding of the system's past.

Paleohydrologic methodologies that deal with ground water are grouped into three categories: isotopic, physical and geochemical. Isotopic methodologies include the wide variety of analyses available on inert gases, parent/daughter relationships, and isotope ratios. Studies that rely on physical evidence include interpretation of ancient karstic landforms through direct observation, location of paleosprings, and indicators of past water levels in exposed formations. Geochemical methodologies include kinetic studies, salinity and resistivity measurements, and ion ratio measurements. Most often, several of these methodologies are used in parallel to verify or improve the reliability of the conclusions. This section does not test the mechanics of each method, but rather presents the various techniques, their possible applications, and their limitations.

ISOTOPES IN PALEOHYDROLOGY

Eleven of the sources identified through the literature search were analyzed for this section on isotopes in paleohydrologic studies. Eleven sources obviously do not make an exhaustive list, but the techniques discussed in these

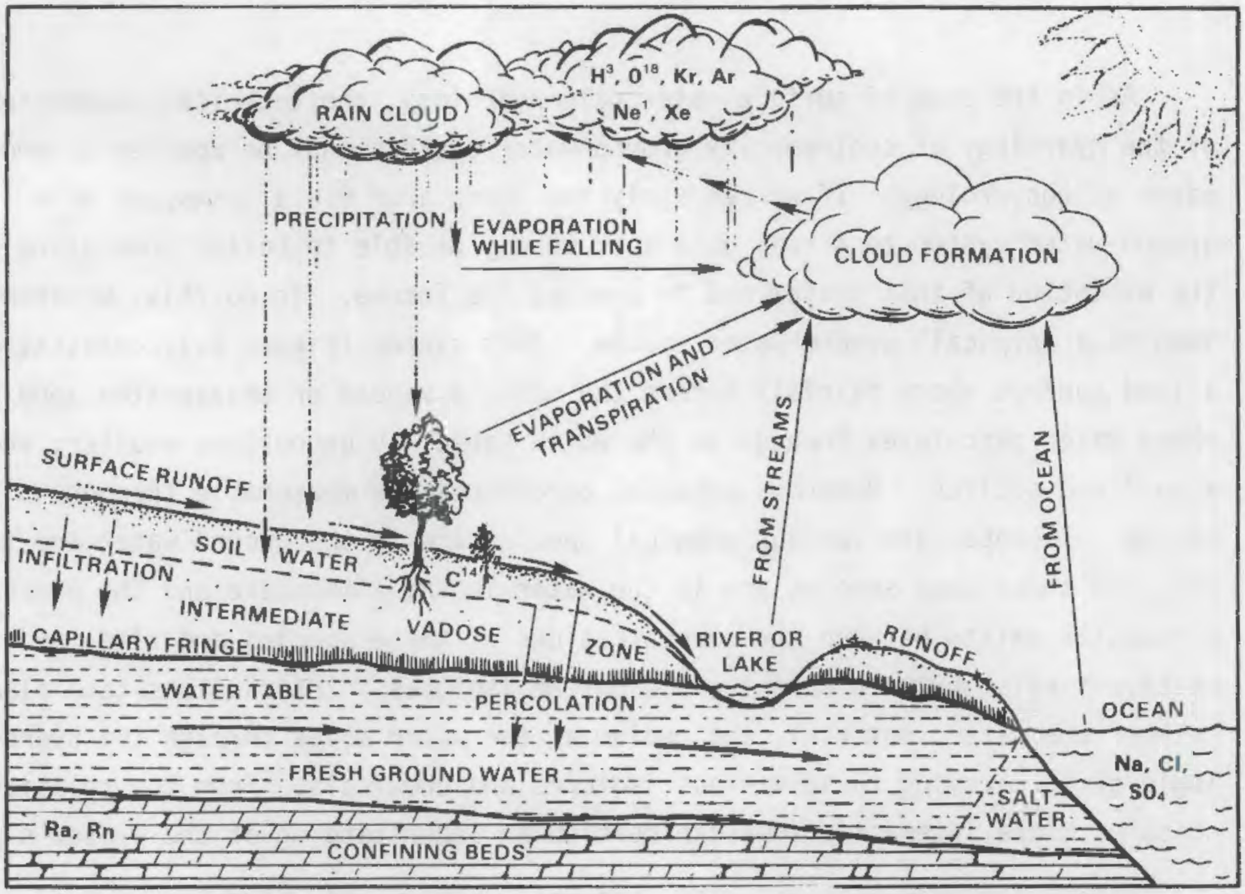

FIGURE 6.1. Ions and Isotopes in the Hydrologic Cycle

sources appear to include most of those used in present day research. Several prominant authors were queried during the research for this paper, including Peter Fritz of the University of Waterloo, Stanley Davis of the University of Arizona, and Robert Gilkeson of the Illinois Geological Survey. These researchers were asked to provide any insight into other techniques for paleohydrologic investigations, and their comments have been included in this chapter.

The isotopes that are most commonly used in hydrologic analyses are helium (He), krypton (Kr), argon (Ar), neon (Ne), xenon (Xe) radium (Ra^{226}), radon (Rn), carbon (C^{14}), oxygen (O^{18}), hydrogen (H^3) and H^2 uranium (U^{235} and U^{238}), chlorine (Ci^{36}), selenium (Se^{79}), and iodine (I^{129}). Mazor (1976) divided this list of isotopes into six groups, creating a convenient format to discuss each of their applications in paleohydrologic techniques. These groups are discussed below.

Stable hydrogen and oxygen isotopes, deuterium (H^2 or D) and oxygen 18 (O^{18}) have been used by many researchers to determine the origin of ground water, climate change, and ground-water movement. The oceans are the source for most of the precipitation that eventually becomes ground water. The hydrogen/oxygen stable isotope ratio in the ocean is constant. The clouds formed from water evaporating from the oceans will have a stable isotopic ratio of O^{18} to D. As the clouds move inland and increase in altitude, the heavier isotopes precipitate first, leaving the remainder of the cloud depleted in those isotopes. As a result, rain farther inland or at higher elevations becomes lighter and is distinct from rain at other locations. These distinctions become somewhat confused because of climatic effects, but annual averages tend to bear out the distinctive nature of waters at the different locations. Once the water infiltrates into the ground, these isotope ratios become fixed and the water has a distinctive "fingerprint" that indicates its origin.

Issar, Bein and Michaeli (1972) used O^{18}/D ratios to confirm C^{14} dating of fossil water in the Upper Nubian sandstone in the central Sinai. Fritz, et al. (1976) used the same techniques to distinguish the origin of waters to analyze storm runoff events. This technique has been used in numerous other applications, discussed in IAEA (1979).

Tritium occurs in the hydrologic cycle from both man-made and natural sources. Hydrogen (H^3) is produced naturally by the interaction of cosmic rays and nitrogen. The natural concentration of tritium in the atmosphere was about 5 to 20 tritium units (TU) before atmospheric testing of thermonuclear bombs, which began in 1952. Because the half life of tritium is about 12.3 years, waters that were recharged before 1952 should have tritium concentrations on the order of 2 to 4 TU. After testing began, values for tritium in the atmosphere rose to 800 TU in the northern hemisphere and to 60 in the southern hemisphere. This addition of tritium to precipitation allows researchers to group water into two age groups: water with tritium content less than 2 TU is pre-1952; water with tritium content significantly higher is post-1952. Relative concentrations of tritium and carbon-14 can be used to further refine age dating of recharge water (Mazor 1976). Water with high tritium and high C^{14}

concentrations is post-1952; water with low tritium but high C^{14} concentrations is older than 1952 but younger than 30,000 years before present; water with low tritium and low C^{14} concentrations is older than 30,000 years before present.

Age dating of ground-water using C^{14} is complicated by several mechanisms: 1) exchange and dissolution of old carbon from the soil and rocks in an aquifer, 2) fluctuations of natural carbon in rain, 3) additions of C^{14} into the atmosphere from bomb testing, and 4) altering of atmospheric carbon by the burning of fossil fuels. Nevertheless, C^{14} dating and testing is a common and useful tool for ground-water research. Mazor (1976) discussed the usefulness of C^{14} dating when combined with tritium measurements. Geyh (1972) combined C^{14} dating and tritium measurements to determine ground-water recharge rates in Central Europe and Brazil. A number of other applications are listed in IAEA (1976), along with the problems associated with those applications of C^{14} dating.

Radium-226 (Ra^{226}) is a product of the uranium-238 (U^{238}) decay series; in turn, it decays to radon-222 (Rn^{222}). The geochemical path of these isotopes is: common igneous and sedimentary rocks contain U^{238}, which is incorporated into the mineral crystal lattices and is slightly dissolved by ground water. The Ra^{226} formed by the decay of the U^{238} is easily dissolved (especially in Cl-rich water), and the Rn^{222} formed by the decay of Ra^{226} is more easily dissolved. The dissolution of these isotopes is controlled by three factors: 1) time of contact of water to rock, 2) temperature (increased temperature increases solution), and 3) the amount of Cl^- in the ground water.

Radium-226 can serve as a hydrological tracer by its presence in above normal concentrations (50 to 100 pCi/ℓ), indicating a high age; the ground water is trapped or is slow moving. Also, Ra^{226} can serve as a tracer in determining mixing of deep-seated and shallow ground water, an example being where high concentrations of both tritium and Ra^{226} are found.

Andrews and Lee (1979) discussed the use of Rn^{222} in the Bunter Sandstone in England. The amount of Rn^{222} in the groundwater of the Bunter Sandstone is attributed to the aquifer variability around the well sampling points. The short half-life and the water/rock contact time determine the amount of Rn^{222} that will be found in groundwater. If the water were to flow as fissure flow from a great distance, the amount of Rn^{222} would be reduced due to the low surface area of the fissures. If the water moves through the granular material of the aquifer, it can move only a short distance before the effects of half-life determine the Rn^{222} concentration arriving at a well point.

Helium-4 (He^4) is produced in the decay series of U^{238}, U^{235}, and Th^{232}, which occurs in most igneous and sedimentary rocks. It is mobile and enters the water surrounding these rocks and is easily measured by mass spectrometry. The amount of He^4 in the ground water is controlled by the length of time that the water is in contact with the rock, and by the temperature of the system: the higher the temperature, the greater mobility of He^4. Radiogenic He^4 is a good ground-water tracer because the atmospheric contribution of He^4 is negligible. Radiogenic He^4 can be used as a tracer in several ways: high concentrations of He^4 indicate older water; higher concentrations of He^4 may indicate a high temperature environment at one time or another in the movement of the ground water; and high He^4 concentrations found in conjunction with high tritium concentrations can be used to date and trace ground-water movement.

The atmospheric noble gases equilibrate very rapidly with water, are temperature dependent, and are therefore useful as paleoclimatic indicators. Mazor (1976) listed four uses for the noble gases in paleohydrology: 1) to demonstrate the meteroric origin of thermal waters; 2) to deduce the ambient paleotemperatures that prevailed in the recharge area; 3) as a prospecting tool to determine thermal waters that are fed by superheated reservoirs versus those fed by medium-temperature reservoirs; and 4) as a tool for tracing steam production in geothermal fields.

Rozanski and Florkowsi (1979) described a specific technique for dating ground water using krypton-85 (Kr^{85}). This technique requires the collection of a 200- to 300-liter sample of water, heating it, and spraying it in an evacuated chamber to collect the gases. Higher concentrations of Kr^{85} indicate younger water, whereas lower concentrations indicate water that has been out of contact with the atmosphere.

Loosli and Oeschger (1978) discussed a similar technique using argon-39 (Ar^{39}). This technique also requires a large water sample (15 m^3) and is subject to even more contamination. Both the Kr^{85} and Ar^{39} techniques offer an alternative to tritium as a young water tracer.

Chlorine-36 is produced in the upper atmosphere by spallation of ^{40}Ar. It is also produced in the subsurface by the following reaction:

$$^{35}Cl + n \longrightarrow {}^{36}Cl + \gamma$$

If the production of ^{36}Cl has been constant in the atmosphere and the aquifer to be examined is well defined, an approximate age can be determined from a sample of 4 or more points. Davis (1979) estimates that ^{36}Cl will be useful for dating water between 50,000 and 1,000,000 years old.

Davis (1980) suggests selenium as a potential groundwater dating mechanism. The amounts of selenium that may be found in groundwater have not been determined yet, but its long half life and solubility in water make it a good candidate for groundwater tracing.

Iodine-129 (I^{129}) is another isotope that has potential for being a good ground-water age indicator. The primary source of I^{129} is cosmic ray activation of stable Xenon. The I^{129} descends to the earth, mixes with the iodine carried with the water vapor from the ocean, and infiltrates into the ground-water system. Davis (1981) discusses problems caused by halite dissolution and source mixing but concludes that this isotope still has potential for ground-water dating.

GEOCHEMICAL TECHNIQUES IN PALEOHYDROLOGY

The dissolved ion concentrations found in groundwater vary considerably because of the many contributors to the system. Rain water is exposed to dust, atmospheric gases, sea spray, and man-made pollutants. This same water is exposed to the various components of the soils, plants that live in the soil, and the rock beneath the soil before it enters a ground-water system. Salt content can be altered by evaporative processes on open bodies of water and in the aerated zone of the soil. The exact nature and origin of a groundwater can be further complicated by the mixing and diluting of waters through fracture zones and aquitards. In spite of the problems in interpreting geochemical data, several paleohydrologic investigations have used geochemistry to interpret ground-water systems. Several of the sources identified through the literature search were analyzed for this section on geochemical techniques in paleohydrology. As in the section on isotope techniques, this list is by no means exhaustive, but it does give perspective to the types of work that are being performed.

Chebotarev (1955) examined thousands of chemical analyses of ground water from Australia and observed that the dominant anionic species change as ground water moves on a regional scale. The change generally follows the sequence:

$$HCO_3^- \rightarrow HCO_3^- + SO_4^{2-} \rightarrow SO_4^{2-} + HCO_3^- \rightarrow SO_4^- + Cl^- \rightarrow Cl^- + SO_4^- \rightarrow Cl^-$$

The reason for this observation is apparent when one examines the availability and solubility of the sources of these ions. Bicarbonate (HCO_3^-) is more widely available in recharge areas but has lower solubility than sulfate (SO_4^{2-}) or chloride (Cl^-). Whereas, chloride has very high solubility, but is usually not present in recharge areas because it has already been dissolved and transported. If recently recharged water is in contact with highly soluble minerals such as halite, the water will be dominated by chloride. On the other hand, very old water in crystalline rocks may be dominated by carbonate. Therefore, the evolution sequence given above is only useful when examined in light of the specific geochemical environment.

A decrease in redox potential has been noted as water flows through some aquifers. Germanov et al. (1958) were first to note this trend. Oxidation of organic matter is probably the cause (Freeze and Cherry 1979). This phenomena does not occur universally but could be useful in distinguishing older water is some aquifers.

LeGrande (1958) presented one of the more simplistic applications of geochemistry to paleohydrology. Ground water taken from North Carolina wells was analyzed for sodium, calcium, silica, total dissolved solids, and pH. On the basis of the chemical and geologic analyses of the areas from which the samples were taken, a model was developed that was used to predict the geology of the source area for other ground-water samples. This analysis divided the water of North Carolina into those found in igneous and metamorphic rocks. Those waters with the higher concentration of minerals and higher pH were found in the more mafic gneisses, diorites, and andesites. Those water analyses that showed lower pH and less hardness were characteristic of the igneous rocks. These simple techniques are easily applied to other situations.

Parker (1969) used similar techniques to determine the history of ground-water flows in the East Texas Basin. Chemically distinct water was traced by ionic composition. Parker's analysis was somewhat different in that he used Schoeller diagrams (Freeze and Cherry 1979) to distinguish variations in the ion concentrations in each of the waters analyzed. Schoeller diagrams can accommodate and display large amounts of data and can be used to check similarities or differences in data. Parker concluded on the basis of the rock composition of the area, the geologic history, and the water quality comparison, that the waters of the aquifers were mixed in the upper portion, whereas the waters in the lower portions of the aquifers were distinct.

Hem (1970) provided data on the likely sources of major, minor, and trace constitutents in both ground water and surface water. Chemical reactions which affect the occurrence of each species were discussed and many case histories were presented. He also discussed various methods of organizing and presenting water-chemistry data. Many of these methods are applicable to paleohydrologic studies because the chemical composition of ground water gives clues to its age and the minerals with which it has been in contact.

Issar, Bein, and Michaeli (1972); Kafri and Arad (1979); and Nathan and Fructer (1974) all used chemical relationships in their studies to infer the geologic history of water in various settings. Mazor (1976) discussed the use of multitracing and multisampling in hydrologic studies.

Geochemical techniques are commonly used in conjunction with isotopic techniques in studying a ground-water system. Egboka (1981) used the distribution of tritium to distinguish water recharged since 1953 in two shallow aquifers from older water in the same aquifers. The distribution of the stable isotopes oeuterium and oxygen-18 were used to determine areas of evaporation from the aquifer. This information was used simultaneously with chloride and sulfate distributions to identify areas of recharge and discharge. A plume of contaminated water caused by an abandoned landfill was also delineated from the chloride and sulphate distributions.

The geochemical techniques examined so far are based on the chemical composition of water in the aquifer. Clues to paleohydrologic conditions may also be found in the aquifer matrix. Deposition of minerals occurs when the water becomes supersaturated. This may be caused by changes in pressure or temperature, evaporation, or the dissolution of a more soluble mineral containing one of the precipitation reactants. Much study has been devoted to the formation of economically important ores through such processes (Barnes 1967). White (1968) noted that saline solutions will dissolve and transport some minerals that are practically insoluble in pure water. The occurrence and chemical composition of evaporite deposits are also useful in determining ancient patterns of surface drainage. Kazory et al. (1968) discussed the incidence of salt deposits in geologic time.

U.S. Geological Survey researchers including Bill Back, Ivan Barnes, Bruce Hanshaw and John Hem were contacted in order to identify new techniques and current areas of research which have not yet been published. Geopressured zones in the Gulf Coast area of the United States are being studied, and may yield information on ancient hydrologic conditions. Freon compounds have been introduced to the environment by mankind within the last few decades and may prove useful for dating and tracing of groundwater. A large amount of research is also being devoted to developing a better understanding of chemical processes in the aquifer. Reaction kinetics are being studied as well as the solubilities of minerals in complex solutions. These data are being applied to the development of numerical models which will predict the chemical composition of groundwater as it flows through a given system.

PHYSICAL TECHNIQUES

Paleohydrologic ground-water methodologies based on physical evidence rely on the uniformitarian principles developed by geomorphologists. These principles are to apply the knowledge of the world as it exists today to the evidence observed in the geologic record. To this end, a number of researchers have been identifying past geologic conditions by comparing them to analogous conditions today.

For example, paleokarst landforms and their associated geomorphic records can be used to infer past ground-water conditions. Sinkholes, common karst landforms, may be divided into three general types according to the conditions under which they develop. Solution sinkholes are formed by the solution of a limestone surface to form a depression. Collapse sinkholes are formed by subsurface solution and the subsequent collapse of the cave roof. A third type of sinkhole forms in thin-bedded limestones where the roof of a cave collapses incrementally, forming a steep-sided hole or cenote. The shapes of the caves beneath the holes, and the relative smoothness of the sides of the sinkholes, can tell the history of ground-water fluctuations in the vadose zone. Karst landforms also include gullies and valleys with vertical heads and sidewalls and nearly flat floors, which occur along solution escarpments.

Stringfield, LaMoreaux and LaGrande (1974) examined karst landforms in both arid and humid terrains to determine the paleohydrologic regimes that formed them. Each of the areas examined in the arid zones have evidence that the karst formed during a more humid period. The extent of karstification and the geologic history as evidenced in the stream channel and shore sedimentary record were used to determine the hydrologic conditions of the past.

Bogli (1980) discusses the effects of corrosion on cave walls and the relation of corrosion to the presence of a phreatic surface in the cave system. Water that is not exposed to the atmosphere becomes neutral as it moves through the system, while water exposed to air absorbs CO_2 and becomes acidic. The acidity or corrosive nature of this water is seen as lines in the sides of caves or in non-symmetrical cave passages.

Schmidt (1976) also worked with carbonate solution systems to determine paleohydrologic conditions. His examination of the passages and fill materials in Laurel Caverns in Pennsylvannia enabled him to determine that the caverns formed under hydrologic conditions very similar to those currently found in the area.

Burdon and Al-Sharhan (1968) discuss a proposed investigation of the Damman limestone aquifer in Kuwait. They discuss the use of aquifer pump testing to determine transmissivity values, T, for several areas. Paleokarstic features would have higher T values. Borehole logs and resistivity and geochemical data were to be collected to complement the pump test data. No indication of a follow-on report was found in our bibliographic search.

White and Deike (1964) discuss the use of flute marks and scallop marks on cave walls as a means to determine direction and velocity of underground streams. They determined that the direction of flow and the gradients in a cave system were controlled in part by stream piracy and changes in base level.

Numerous other studies of karst landforms have been carried out using sedimentological, paleonotological, and speleological techniques. Very often this research is hidden within other publications and is not identified as "paleohydrologic" research. This portion of the report must, therefore, be assumed to be incomplete despite the manual search that was conducted (see Section 3.0).

Winograd and Doty (1980) describe both macroscale and megascale morphologies in the Ash Meadows and Death Valley areas that are indicative of fossil spring deposits. These morphologies include fossilized vegetation mats, tufas draped over existing topography, and tufa mounds. Calcite veins and strandlines are also indicators of paleo ground-water levels. They used these phenomena to develop a paleohydrologic description of the Nevada Test Site and the surrounding areas, and incorporated the resulting differences in boundary conditions (from the present ones) into a computerized flow model to estimate the differences in ground-water flow.

Other physical techniques that have been used in paleohydrologic studies are consolidation tests, grain-size distribution analyses, and petrographic analyses. Soderman and Kim (1970) examined the St. Clair till in southwestern Ontario to determine the causes of the discrepancies between the observed and predicted settlement rates of structures bedded in the till. They determined that the till was overconsolidated at depth because of groundwater lowering in the past. The ground-water lowering was inferred from staining of sediments by oxidation of iron.

<u>Summary</u>

Three groups of techniques have been identified as being applicable to ground-water paleohydrological studies. Those techniques using isotopes use transport phenomena and decay times to determine residence time and travel time for water. Geochemical techniques can be used to determine the recharge area or the types of materials that a ground water has flowed through. Physical techniques demonstrate visible changes in materials that result from the past action of ground water. Most paleohydrologic studies use a combination of techniques to determine past conditions.

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16. ABSTRACT *(200 words or less)*

Pacific Northwest Laboratory conducted a literature review to identify methodologies that could be used to interpret paleohydrologic environments. Paleohydrology is the study of past hydrologic systems or of the past behavior of an existing hydrologic system. The purpose of the review was to evaluate how well these methodologies could be applied to the siting of low-level radioactive waste facilities.

Paleohydrologic interpretations are uncertain because of the effects of time on hydrologic and geologic systems and because of the complexity of fluvial systems. Paleoflow determinations appear in many cases to be order-of-magnitude estimates. However, the methodologies identified in this report mitigate this uncertainty when used collectively as well as independently. That is, the data from individual methodologies can be compared or combined to corroborate hydrologic predictions. In this manner, paleohydrologic methodologies are viable tools to assist in evaluating the likely future hydrology of low-level radioactive waste sites.

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